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Experiments in Planetary and Related Sciences and the Space Station

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1.0 INTRODUCTION

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During the last several years, studies have been undertaken to identify the potential science activities that could be conducted in the environment afforded by an Earth-orbiting space station. Activities related to planetary science that are being considered for the Space Station include using the Station (1) as a platform for planetary observations, (2) as a staging base for various lunar and planetary missions, (3) to collect "dust," and (4) as an environment for carrying out experiments. This report concerns the fourth topic.

Many planetary environments involve gravitational accelerations less than that of Earth. The Space Station could enable experiments to be conducted in which gravity (g) is a critical term in certain planetary processes, especially for planetary experiments requiring extremely low gravity environments such as comets and asteroids. In other experiments, g may not be a critical term for study, but its near-absence on Space Station may enable experiments to be conducted which cannot be done on Earth. Some of the general experiment areas that have been suggested include impact cratering, experimental petrology, and the formation and interaction of small particles (e.g., planetary ring dynamics).

Numerous workshops were held to provide a forum for discussing the full range of possible experiments, their science rationale, and the requirements on the Space Station, should such experiments eventually be flown. These workshops, sponsored by NASA through Arizona State University and the Lunar and Planetary Institute, were open to all interested scientists. During the workshops, subgroups met to discuss areas of common interest (impact cratering, aeolian processes, particle formation and interaction, and planetery materials/miscellaneous). This report is the result of the deliberations of a workshop held at Arizona State University on September 15-16, 1986; it compiles summaries from each subgroup and abstracts of contributed papers.

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2.0 PLANETARY IMPACT EXPERIMENTATION

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2.1 Introduction

Impact processes have operated in the Solar System from the time of formation to the present, at all scales, and on every solid body. Evidence of its effects are apparent in virtually every lunar sample and meteorite, and contributions to the cosmic-dust complex by impact are not unlikely. One of the most dominant influences on the final outcome of an impact event is the magnitude of the local gravitational acceleration (g). Furthermore, a variety of target configurations are possible across the wide range in g existing throughout the Solar System. Most experiments intended to examine the role of gravity in impact processes and to simulate some of the important target configurations in the Solar System have been severely limited or rendered only partially successful by the 1-g environment in which they have been attempted. The advent of the Space Station has provided the potential foundation upon which an impact facility could be constructed to resolve many persistent and critical questions. Specifically, by supporting laboratory studies that would address outstanding problems in accretion dynamics, asteroid evolution, cratering at very low g-levels, and regolith processes on small bodies, the Space Station would permit experimentation that is virtually impossible to perform anywhere else.

The Role of Gravity in the Impact Process

A short review of the effects of gravity on the impact process will be presented in order to establish the context for subsequent discussions. The bulk of our understanding as it is presented here reflects the results of theoretical work (particularly computer-based models and analytical approximations), laboratory experimentation (predominantly at 1-g and higher accelerations), and planetary observations.

Except for its influence on the final velocity of early ejecta, gravity has little effect on phenomena that occur during the initial stages of projectile contact and penetration: the stress field and material properties are the dominant factors at these early times. As the shock front propagates from the impact area, it encompasses a growing volume of material and, because of conservation of energy, decreases in intensity. Except for minor effects such as self-compression of the target, the rate of stress decay is essentially independent of g. When gravitational forces acting over distances similar to the dimensions of the final crater are greater than those due to the target's material strength, gravity assumes a major role in governing subsequent events. Gravity constrains the motions acquired by the shock-mobilized material, and dominates other factors in determining the volume of material removed from the cavity via ejection as opposed to that simply displaced from its initial location by compression. (The degree to which g must be reduced before "low-level" forces -- such as electrostatic attraction -- begin to control crater dimensions is unknown.) It is likely that gravity readjusts the shape of the crater even as the cavity is growing. When the gravitational acceleration is sufficiently high relative to material properties, these modifications become manifested in large craters as terraced walls, flat floors, and central uplifts. The strength of the gravity field also determines the ballistic range of ejecta. If the velocity of ejection were high enough, a reimpacting fragment would begin the formation of a secondary crater, during which the basic process would be repeated, albeit at a reduced intensity and a smaller scale. At lower velocities, simple mixing and deposition would be the rule.

Additional consideration must be given to the small bodies of the Solar System. Initially coherent objects could be severely fragmented by a single large impact or through repetitive pounding by smaller events. Such bodies would be held together not by material strength, but by their own gravitational fields. If no such effect were to occur, it is likely that many members of the present asteroid population would not exist today, due to their dispersal during major collisions. It is possible that an unconsolidated object could be disrupted by an impact below some threshold, only to be "reconstituted" by virtue of its own gravitational field.

Gravity and Impact Phenomena: Geological Aspects

While the masses of ejected and displaced material are controlled by g, the final geometry of the stress field is not. Insofar as the initial locations of shock-metamorphosed material are strongly tied to the geometry of the stress field, they are also independent of g. Thus, the dispersal of shock-metamorphosed material (impact melt, for example) might depend on gravity; if g were very low, highly shocked material might escape from the target body completely. This combination of effects might cause deficiencies of impact-melted material in regoliths on small bodies. If these fragments were ejected at speeds above the target's escape velocity, they could become meteorites or part of the cosmic-dust population. At lower speeds, the ejecta would return and comprise the crater's ejecta "blanket." The relationship between ejection velocity and g is critical in determining whether a regolith on a small body can persist, whether it would be removed by repetitive impacts, and how the shock-levels recorded in its components would compare to those in its lunar counterpart.

The rate and depth of regolith mixing is dependent on the volume of ejecta represented by the total volume of craters formed in the regolith. The volume of ejecta and the manner in which it translates into ejecta-blanket thicknesses is important in shielding samples from the solar wind, as well as from solar-flare and cosmic radiation. (These particles and their effects are used to decipher the evolution of the regoliths which they have affected as well as to probe the histories of the radiation sources themselves.) Autochthonous displacement during cavity formation in a porous regolith results in compaction and therefore a net increase in density. Not only will this alter the characteristics of subsequent cratering, but it will also encourage more effective shielding by increasing the amount of mass in a given column of material.

Having been disrupted by an impact with insufficient energy to disperse it completely, an initially differentiated asteroid would "reaccrete." During reaggregation, once differentiated layers would be mixed. A reflectance spectrum of such an object would not be representative of a single meteorite type, and potential meteorites derived from its "new" surface would probably be unusually polymict.

2.2 The Space Station and Impact Experimentation

As will be discussed in a subsequent section, it is possible to perform low and microgravity experiments with existing facilities and aircraft. Invariably, however, these capabilities fall short of those required for high-quality investigation of most of the processes and problems described above. Drop towers provide zero-g, but only for a short period of time; not only is the duration of possible experiments limited, but constraints are placed on the types of targets that could be employed. The NASA KC-135 Reduced-Gravity Aircraft can provide longer time in which to work, but atmospheric turbulence typically causes "noisy" accelerations, particularly at the lower g-levels. The Space Station, however, would provide a unique platform for experiments of extended duration at different g-levels. This exciting potential is due to three basic factors: (1) free-floating targets could be impacted to study their disruption and subsequent motions; (2) targets with more realistic or more appropriate structures than those employed in the 1-g laboratory could be fabricated and used in a variety of microgravity experiments; and (3) the actual environments on small planets, asteroids, and satellites could be simulated with high fidelity. Points (1) and (2) could be accommodated on the IOC Space Station at a simple level, while point (3) will require a means of generating "artificial gravity", more than likely through centrifugal methods. In no realistically conceivable case would all three capabilities exist in any other single facility, and none of the three could be supported to yield the requisite level of quality anywhere else.

Potential Experimentation: Selected Examples

A wide range of experiments that might be conducted with an impact facility on the Space Station has been proposed, debated, and discussed over the last few years. In the interest of brevity, however, only a few examples will be presented here.

Late-Stage Accretion Processes -- During the period between the beginning of accretion in the presolar nebula and the late stages of planet formation, an evolutionary trend between constructive and destructive processes occurred. As more of the dust and gas was absorbed by growing planetesimals, average encounter velocities grew in response to the increasingly concentrated gravitational sources, and relatively gentle coagulation was gradually replaced by high-velocity impacts.

Representative Questions: At what velocity measured relative to typical encounter velocities did the transition between net accretion and disruption occur? What factors controlled the transition between the two competing processes? Do relics of this period remain and, if so, what might be their observable characteristics? Previous Experimentation: Hartmann [1978] has performed relatively low-velocity experiments using rock, H_2O-ice, and "dirt clod" projectiles and both rock and particulate targets to map the potential for accretion vs. encounter velocity. Numerous experiments at higher velocities have been conducted to study the destructive aspect [see the review of Fujiwara, 1986]. Schultz and Gault [1986a] have impacted particulate "clouds" into particulate targets and found relatively large, "fairy-castle" structures hitherto unobserved with any other projectile-target combination. Potential Space Station Experiments: The difficulty in constructing low-density targets and projectiles in a 1-g field precludes studies using a type of configuration that might have been abundant during accretion. Indeed, the bulk of probable cosmic-dust grains collected by aircraft are porous aggregates [e.g., Brownlee, 1978]. The Space Station environment would encourage the use of similar assemblages in both low- and high- velocity experiments. Particulate "clouds" also could be employed.

Asteroid Evolution -- The rotational characteristics of observed asteroids are well documented, but the factors involved in initiating these spin rates are not fully understood. Even if these objects had formed with residual rotations, the spin angular-momentum vectors almost undoubtedly would have changed as a result of subsequent impacts. The probable existence of highly disaggregated asteroids and planetary satellites (as described in an earlier section) implies targets with little or no cohesive strength. Impacts into such bodies will result in a transfer of momentum and will generate severe stresses that would lead to further fragmentation and possibly destruction of the object as an entity. Representative Questions: How does the thickness of a fragmental layer affect momentum transfer during a major collision? Can the angular momentum gained during this type of event be sufficient to rip away that layer, or can this be accomplished only by shock-induced spallation? How does a weakly-bound asteroid break up catastrophically, and what are the relative velocities of the fragments? What is the size of the largest crater that can form on one of these "rubble piles" without destroying it? Knowing this, what does the crater Stickney reveal about the internal strength and structure of Phobos? Would a small, fast projectile be as efficient as a large, slow impactor in disrupting one of these bodies? Previous Experimentation: A variety of experiments treating collisional disruption have been performed with solid target materials [see the review of Fujiwara, 1986]. Some work into the transfer of momentum in solid [Gault and Heitowit, 1963] and particulate targets [Davis and Weidenschilling, 1982; Gault and Schultz, 1986; Schultz and Gault, 1986b] has also been performed with ballistic pendulums. Interpretation of experiments using ballistic pendulums is often made difficult by the large pendulum masses and reimpacting ejecta that contribute to the total momentum transfer. Generally, only two components of momentum can be examined in a given experiment. Potential Space Station Experiments: The ability to employ free- floating targets of widely differing compositions and structures would permit experimentation across the spectrum of possible target configurations, including noncohesive or even liquid targets that are impossible to use on the ground. Six degrees of freedom (three each in rotation and translation) would allow documentation of all momentum components in each experiment. Ejecta would not return to the target in microgravity experiments, and the extended time during which the target could be observed would permit detailed observations of its motion following the impact.

Dynamics of Crater Ejecta -- Predictions of the role of g in influencing ejection velocities have been made on the basis of dimensional analysis [Housen et al., 1983], but little data exist for testing and calibrating the theory. Regolith evolution on and loss from small bodies are highly dependent on ejection velocities which, in turn, should be dependent on g. In addition, the relationship between the stress field and the final volume and velocities of ejected material is related in no small way to the amount of highly-shocked material that can be retained in asteroidal regoliths. Representative Questions: How are ejection velocities affected by g, especially during impacts into small objects? How large must an asteroid be to retain most of the material melted in a cratering event? Would there be a general relationship between g and trends in spectral reflectance? What fraction of the cosmic- dust population can be attributed to ejecta from craters on asteroids? How much ejecta from a given crater escapes Phobos and Deimos to undergo subsequent reimpact via Soter's [1971] mechanism? Previous Experimentation: Ejecta velocities for small craters in rock [e.g., Gault et al., 1963] and sand [Oberbeck and Morrison, 1976] have been measured in the laboratory; only the sand case would be affected by g at this scale. A variety of studies has also been performed on ejecta from explosion craters, but because of significant mechanical differences between explosions and impacts, their applicability to the impact process is not complete. Potential Space

Station Experiments: Ejecta dissectors or slit-illumination techniques would be employed at different g-levels to segregate planar segments of ejecta plumes for photography and subsequent analysis. The initial points of origin of individual fragments of ejecta could be traced using established methods, such as layered targets, columnar markers, and/or individual "tracer" particles embedded in the target. Ejecta catchers could be used to measure ejecta mass as a function of range to evaluate "blanket" thicknesses and the contribution from each layer at a given range.

Regolith Processes on Small Bodies -- Most stony meteorites appear to be samples of very complex regoliths. Lunar samples have provided fundamental information about regolith evolution on a relatively large body, but important differences exist between the two sample types. Meteoritic breccias possess features common to their lunar counterparts. The meteorites, however, appear to be derived from coarser regoliths, are generally more weakly shocked, have lower solar-gas abundances by orders of magnitude, and were exposed at the surfaces of their respective parent bodies for much shorter periods. Nontrivial differences in their original environments are indicated. While much remains to be learned about the impact process on the Moon, even less is understood about the effects of impact in asteroidal environments. Because of this circumstance, the questions to be answered seem simplistic in comparison to those posed above. Relevant Questions: How small must g be before "low-level", non-gravitational forces begin to dominate cratering phenomena? Is this even a realistic consideration? Will fine-grained material be retained in sufficient quantities on small bodies to generate a regolith remotely similar to that on the Moon? If so, what are the relative fractions of excavated and compressed material during a given cratering event? Would such a regolith undergo net compression due to repetitive impact, or would it actually become more porous during the emplacement of low-velocity ejecta? Will gravitationally-retained impact melt on an asteroid or satellite be dispersed over greater areas than on the Moon? What are the potential effects of these phenomena on reflectance spectra? Previous Experiments: A large number of experiments have been performed with existing facilities, leading to much of our current practical knowledge of cratering processes; they are too numerous to be cited here. Very few have been conducted at reduced-g. Although it is possible to perform reduced-g experiments with existing facilities, as has been done with the Ames Vertical Gun [Gault and Wedekind, 1977], the durations of the lowest g-levels are very limited. Low-velocity experiments also have been conducted on the NASA KC-135 Reduced-Gravity Aircraft [Cintala et al., this volume] at relatively high atmospheric pressures. Potential Space Station Experiments: Assuming that the desired range of g-levels would be available, an exploratory series of impacts would be performed at accelerations of 0.1 to 0.01 g. In addition to those listed in the Ejecta Dynamics section, parameters such as crater dimensions, subsurface displacements, distribution of shocked material, target grain-size effects, and density changes in the target will be analyzed. Should gravity continue to dominate the process at the lowest g-level employed in the series, further reductions in g would be applied in an effort to determine the limits of influence.

In listing the types of experiments that could be performed with a Space Station facility, it is natural to recall previous activities in ground-based laboratories. In doing so, however, one rapidly comes to the realization that, had a similar exercise been attempted in justifying the proposed construction of the NASA Ames Vertical Gun, for instance, foresight would not have made a strong showing. That facility, built to evaluate impact cratering as a potentially important process active on the lunar surface, has since been used in a myriad of studies that could not have been predicted at the time. Instead of listing those investigations, it will simply be suggested that the use of a Space Station facility would be analogous to that of the Ames and other guns in the sense that many, and probably most, of the experiments that could be performed in the microgravity laboratory have not even been imagined yet.

2.3 Experimentation in Reduced Gravity: Practical Considerations

A low-level effort has been underway since the latter part of 1984 to evaluate the requirements of performing experimentation at reduced-g. These studies have been made possible by the availability of the NASA KC-135 Reduced-Gravity Aircraft, which is the responsibility of the Johnson Space Center and based at Ellington Field in Houston.

The NASA KC-135 Reduced-Gravity Aircraft

The NASA KC-135 Reduced-Gravity Aircraft is a Boeing 707, specially modified to support zero-gravity flight. With only a few passenger seats in the rear of the aircraft, it presents a large volume to the experimenter for hardware and its operation. A typical "zero-g" parabola has a duration of ~23 seconds, while lunar- and martian-g maneuvers can last up to ~35 and 45 seconds, respectively. Due to atmospheric turbulence and density variations, winds, and other factors, a given g-level can be held to within roughly 0.05g; thus, lower g-levels become relatively "noisier" in terms of the targeted accelerations, with the result that the higher g-levels are generally "smoother." Should very low accelerations be required, relatively short periods (on the order of 5-10 seconds) of nearly zero-g can be obtained by detaching the necessary hardware from the airframe and "free-floating" it in the cabin. The desired sequence of maneuvers is determined before flight, although considerable flexibility exists in terms of real-time changes.

The Experimental Hardware

Details regarding the experimental apparatus can be found elsewhere [Cintala et al., this volume]; an abbreviated summary will be presented here to establish a context for the following discussion and comments. The low-velocity impact facility consists of a glass-walled, aluminum-framework box (52 cm x 52 cm x 48 cm) on the top of which is mounted a vertically-oriented Sheridan pellet pistol, modified to be fired electronically. A microcomputer controls event sequencing, which includes camera operation, recording of acceleration and atmospheric pressure data, firing the gun, and recording detector information for determination of projectile velocities. This facility, intended to be flown again in 1986, is limited in terms of impact velocity (maximum of ~130 m/s with lead pellets), lack of a vacuum system (meaning that all impacts take place at cabin-atmosphere pressure, ~0.85 atm), and container size. Nevertheless, a good deal of practical information has been collected thus far. Trends in crater scaling were found to be similar to those found through 1-g and centrifuge studies, with some variations whose causes are not yet established. Crater growth-times tentatively appear to be at variance with both theoretical predictions and extrapolations from ground-based data; this latter observation, however, will require more data before any claims can be made with confidence.

Practical Lessons Taught by the KC-135

Due to the rapid changes in acceleration, activities performed on the KC-135 can be extrapolated to the orbital environment only with some caution. Even so, the aircraft provides information that would be impossible to obtain otherwise. A few points will be presented here.

Scale -- For a given set of impact conditions, a crater will be larger in a lower g-field than a crater formed in a higher g-field. In designing a facility for cratering experiments in reduced gravity, this phenomenon is the cause of what is perhaps the principal experimental concern. Even at the low projectile energies employed in the KC-135 experiments, it is apparent that a larger target chamber and target container is necessary for serious investigations. Craters take so long to grow at the low g-levels that the first -- and fastest -- ejecta to leave the crater has sufficient time to rebound off the chamber walls and impact in the vicinity of the growing cavity. This could become a significant problem in serious attempts to perform cratering investigations. Two independent suggestions have been made, and the ideal solution would employ both. The first is obvious, but the most expensive in terms of volume: make the impact chamber and target containers large. The absolute dimensions, however, are difficult to suggest in the absence of data at low g-levels; conversely, it is entirely possible that the final dimensions of the physical apparatus will dictate the minimum g-level for which meaningful experiments could be conducted.

Employing the second solution would result in an impact chamber lined with mechanical ejecta catchers or deflectors; a sort of "monoclinic honeycomb" would be an example of the kind of device envisioned.

The question of scale persists, however, when the actual growth of the crater is considered. The longer it takes a crater to grow, the more time exists for stress waves to reflect from the container and interfere with the expanding cavity. Again, the lack of data at the low g-levels precludes a meaningful treatment of the problem. Obviously, the ejecta catchers/deflectors would be of little help in this case. These topics will be considered further in a subsequent section.

Experiments employing free-floating targets will require sufficient free space to permit unconstrained motion for a few seconds following impact. Since collisions with rebounding ejecta also would complicate matters, some of the same considerations described above remain applicable in these studies. An additional factor involved in both areas of experimentation is the effect due to muzzle blast from the projectile accelerator. While this point would be academic if an electromagnetic or other "clean" accelerator were used, the use of either a powder or light-gas gun would require both active blast-deflection measures and some distance between the accelerator's muzzle and the impact region. Such techniques exist, and their incorporation is not considered to be a problem.

Free-Floating Targets -- This topic is somewhat more difficult to address specifically, since experiments involving free-floating targets have not yet been attempted. On the other hand, many impromptu experiments using cameras, film canisters, pens, and other assorted objects have been performed during "zero-g" portions of KC-135 flights. These trials have shown that it is difficult to release an object by hand without imparting undesired motions, and there is widespread agreement between those who have been involved in this sort of activity that a relatively motionless release will require a special target-holding and release mechanism. It is intended to attempt experiments with free-floating targets on the KC-135 in the relatively near future; more specific information regarding release methods and other idiosyncrasies inherent in the technique should then be forthcoming.

Time -- Once one is accustomed to the peculiarities, working in the low-g environment is no more difficult than in the 1-g laboratory. Indeed, when it comes to moving massive objects, the low-g case is much less exhausting, and activities can generally be performed at a faster pace. On the other hand, more time must usually be spent overall during a complete experiment in low- or "zero-g" than in the ground-based laboratory. On the ground, the small items necessary in experiment operations (nuts and bolts, film canisters, pencils, tools, etc) can be and usually are left on a workbench or table. For obvious reasons, this cannot be done in zero-g, and stowing each piece of equipment after its use takes time. By the same token, cleanup after each experiment is somewhat more tedious, since dirt and debris do not fall to the floor or a corner of the chamber, but must be removed from what is typically a very hectic three-dimensional volume. The addition of a sensible gravity field, however, alleviates many of these small but irksome problems.

Overall, the tasks requiring more time tend to be offset by those taking less, but the net result still leans toward a longer period of time to perform a given experiment. Nevertheless, the difference is not dramatic. Impact experimentation in a reduced or microgravity environment is by no means an overwhelming proposition; indeed, with a modicum of experience, it is no more difficult than its ground-based counterpart.

2.4 The Road to the Space Station

A variety of studies, discussions, experiments, and workshops over the past two years [see Appendix A] has led to the realization that the planetary impact community cannot claim vast experience in microgravity experimentation. This has resulted in the recommendation that a phased approach toward impact experimentation on the Space Station be adopted in order to gain some of that experience; simultaneously, a base of fundamental scientific knowledge would be obtained. This approach can be divided into four distinct stages which, in the ideal case, would overlap in a temporal sense: (1) "pathfinder" experimentation, both ground-based and on the KC-135; (2) STS experiments; (3) a relatively simple IOC Space Station facility; and (4) a post-IOC, dedicated Space Station Impact Facility. Each stage will provide engineering and other technical information to support the next step in hardware complexity, and also will raise the level of sophistication of the scientific data. It is likely that the first three stages will be undertaken by a few research groups. Although it is probable that a KC-135 facility would be open to interested scientists, the dedicated Space Station impact laboratory would be a national or international facility, for use by all qualified investigators.

The Pathfinder Activities

As discussed above, an array of topics must be addressed before sophisticated experimentation at very low g-levels can be conducted effectively and efficiently; principal among these is the persistent issue of experiment scale. Due to the many questions remaining unanswered with respect to crater scaling, it is likely that the first IOC experiments which will probably be done in a facility of limited size would involve free-floating targets. It is essential, then, that experience be gained not only in assessing the dimensional constraints for the cratering experiments, but also in performing investigations with the free-floating targets. This sort of background information can be obtained only through experimentation, using existing NASA facilities such as the Ames Vertical Gun Range, the Johnson Space Center Vertical Impact Facility, the NASA KC-135 Reduced-Gravity Aircraft, and the various drop towers. The latter two will also be instrumental in providing initial information for the IOC concept.

The STS Experiment Package

Existing drop towers provide a relatively stable zero-g, which is limited in duration to only about 10 seconds; delicate instrumentation would likely be destroyed or heavily damaged upon impact of the experiment chamber. The KC-135, on the other hand, can supply more time but a "noisier" g-level, especially at accelerations approaching zero-g. While they would be very useful for the early development efforts, the next major advance would require investigations on Space Shuttle orbiters. In addition to the greater volume and other support necessary for experimentation, Shuttle orbiters can provide a low-g environment for extended periods of time. Valuable experience would be gained in the areas of handling target materials, target fabrication, testing preliminary versions of the IOC experiment package, and general housekeeping. High-quality data could be expected from these experiments.

The IOC Space Station Impact Facility

As indicated above, this first phase of experimentation on the Space Station will probably concentrate on impacts of free-floating targets for both operational and scientific reasons. Available volume will be limited in the initial stages of Space Station operations. Variable-g capabilities are highly unlikely, and the studies utilizing the free-floating targets would provide an early information return.

The hardware necessary for these experiments could be relatively compact, taking perhaps the space of a double rack (approximately 100 cm x 100 cm x 200 cm); the accelerator might require some small volume in addition to this. In order to minimize the undesirable muzzle-blast complications cited earlier, some distance would be required between the target and the accelerator. This might be effected by pivoting the gun outside the laboratory module via an airlock mechanism, or by mounting it radially outward in the module, perpendicular to its major axis. Should advances in limiting muzzle-blast have been made in the meantime, however, it is entirely possible that the accelerator could be included within the double-rack volume.

This experiment package will possess a vacuum-capable impact chamber, an accelerator able to launch projectiles to velocities between 0.1 and 2.5 km/s, diagnostic instrumentation, and data-collection equipment such as film and video cameras and digital recording devices. It is anticipated that this facility will be a direct outgrowth of the STS package, with improvements made on the basis of that experience.

2.5 The Space Station Impact Facility

The ultimate configuration of the post-IOC Space Station facility is certainly not established and will undoubtedly evolve from that currently envisioned. Nevertheless, the flavor of its desired characteristics can be conveyed by a description of the preliminary view obtained over the past three-years' effort. Generally speaking, five key requirements have emerged: (1) variable-g capability; (2) a large impact chamber; (3) ability to launch a variety of projectile types and sizes over a wide range of velocities; (4) flexibility in fabricating targets of different compositions, structures, geometries, and physical states; and (5) "hands-on" experiment operation.

Variable-g Capability

The ability to subject the target(s) to a preselected g-level is a principal reason for suggesting this facility. The undesired accelerations suffered by the KC-135 at very low g-levels make it extremely desirable to attain and sustain levels between $\sim 10^{-5}$ to 0.2g. This range will permit experiments involving free-floating targets as well as those overlapping the capabilities of the KC-135. The source of the variable g-levels is problematic at present, although it almost certainly will involve the application of centrifugal acceleration. The prevailing view has assumed the undocking and spinup of a habitable module for general low-g operations, a capability which might benefit other user groups. The details of this operation remain to be defined.

Impact Chamber

As cited earlier, a variety of reasons lead to the requirement of a large impact chamber, among them being stress-wave reflections and rebounding ejecta. In addition, a fragment of ejecta can be tracked longer in its trajectory in a large chamber, free-floating targets could be monitored for a longer period of time after impact, more diagnostic instrumentation can be placed in a larger chamber, and more energetic events could be accommodated at lower g-levels. A chamber at least 4 meters in length by 4 meters in diameter would be sufficient to accommodate the potential experiments as currently envisioned. Although this might seem to be inordinately large, a useful analogy can be made with the Ames Vertical Gun's impact chamber, which is 2.5 meters in diameter. Craters formed with the light-gas gun in sand are typically 30-35 cm in diameter, which is one-eighth the diameter of the chamber; rebounding ejecta in this chamber at 1-g are seldom a problem. Identical projectiles at low g-levels, on the other hand, could easily form craters more than a meter in diameter in sand; the 4 meter space station chamber relative to a crater of this size, would be only half as large when compared to the Ames case above. Clearly, a more voluminous chamber would be highly desirable. The facility could conceivably be used in its earlier stages with a smaller chamber inside the laboratory module. It is more likely, however, that the final version will include an attachable chamber via a docking port or an airlock. With this in mind, it is strongly urged that hatches/airlocks at least 1 meter in diameter be included in the module containing the impact facility; a decision implementing the proposed 50- inch hatches would be welcome indeed by users of the impact facility. A suggestion with some potential employs an inflatable chamber fabricated with a tough composite or similar material. It would occupy a small volume when idle, and, with the proper materials and some ingenuity, could even be larger than the minimum size suggested above.

Projectile Accelerators

Not only will a wide range of impact velocities be required by users of the facility (~0.1 to at least 7 km/s), but a variety of projectile compositions (e.g., metal, plastic, glass, rock, etc.) and sizes (small "grains" to spheres or cylinders up to perhaps 2 cm in diameter) will also be employed. In light of present technology, this implies the use of air, powder, and light-gas guns. On the other hand, technological advances in attaining high velocities (rail guns, mass drivers, and electrothermal guns, for example) might well provide alternatives, in terms of efficiency, mass, and/or performance; it is important that the potential incorporation of such accelerators not be excluded from the final design by default. All of the non-induction accelerators produce exhaust gases and debris as by-products of their operation; not only must the contamination of the chamber be kept to a minimum, but the gases must be removed by venting or containment. Experiments involving low-yield explosives might also be performed.

Instrumentation and Support Hardware

Three general categories of instrumentation required will be used for (1) monitoring gun-firing and the chamber environment, (2) recording the impact event and subsequent phenomena, and (3) post-experiment analysis. The first group includes items such as computer-controlled and monitored gun operations and sequencing, flash x-ray generators and detectors, pressure and temperature gauges, and accelerometers. Event recording will be performed by various cameras, including both film and video, with lighting to support very high and relatively low framing rates; additional equipment should include devices such as pressure transducers, multichannel digital recorders, holographic systems, and spectrometers. It is likely that many of these instruments will be controlled and/or monitored by computers, which would also be used for scientific programming in tasks such as data reduction. Post-experiment analysis will require microscopes, various photographic and holographic systems, "scales" for mass determination, and sieves.

Target Preparation and Housekeeping

Additional, more mundane hardware will be required for target preparation, facility maintenance, projectile construction, and the other activities necessary for successful impact experimentation. A brief representative listing in this important area includes a small machine shop, a "workbench," target containers, microwave and thermal ovens, vacuum systems, a freezer, an ice crusher, an oscilloscope, and various temperature and pressure transducers. This sort of equipment would almost certainly be needed by other research groups, and could be part of a shared equipment pool.

Personnel

A minimum of two experimenters equivalent to STS payload specialists will be required for efficient operation of the facility, with two backup specialists on the ground.

2.6 Summary

An understanding of impact processes in low- and microgravity environments would be advanced significantly by the construction and use of an impact facility on the Space Station. It is proposed that initial studies begin as soon as possible in ground-based impact laboratories, on the NASA KC-135 Reduced-Gravity Aircraft, and in existing drop towers. The resulting experience and information base could then be applied toward an experiment package designed for use on Shuttle orbiters to support pilot studies in orbital environments. These experiments, as well as the first efforts made on the IOC Space Station, should involve the impact of various free-floating targets; such studies would yield a substantial scientific return while providing valuable experience and engineering information for use in refining the design of the dedicated Space Station Impact Facility. The dedicated facility should be designed to support impact experimentation, including but not limited to cratering, asteroid and ring-particle dynamics, and accretional processes.

Acknowledgments

This contribution is the culmination of suggestions, comments, and other inputs from a number of people involved in the planetary sciences, and the planetary impact community in particular. Two workshops of the Microgravity Impact Working Group (Table A1) were held at the Johnson Space Center in November 1984 and March 1985, during which much of the fundamental scientific rationale, suggested experiments, and facility requirements were advanced and discussed. Subsequent SSPEX (Space Station Planetology Experiments) workshops in Flagstaff (in 1984 and 1985) and Tempe (in 1986) included valuable discussions both following presentations and between sessions. The original report published as a result of the 1985 SSPEX effort [Schultz et al., 1986] served as the basis for much of this expanded version. Original and insightful comments and suggestions from members of the Review Panel on Space Station Planetology Experiments during the review held at NASA Headquarters (in June 1985) were also helpful in formulating this report. Suggestions made by Special Projects personnel from the JSC Aircraft Operations Division have made an impact on many of the concepts discussed herein. Funding from the Microgravity Sciences and Applications Division at NASA Headquarters provided the opportunity to attempt impact experimentation at reduced-g in the KC-135. The authors are grateful for the interest taken by all of the individuals involved in these groups and organizations.

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3.0 PHYSICS OF WINDBLOWN PARTICLES

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3.1 Introduction

This report describes a laboratory facility proposed for the Space Station to investigate fundamental aspects of windblown particles. The experiments would take advantage of the unique environment afforded in Earth orbit and would be an extension of research currently being conducted on the geology and physics of windblown sediments on Earth, Mars, and Venus. The report reviews aeolian (wind) processes in the planetary context, gives the scientific rationale for specific experiments to be conducted, describes the experiment apparatus (the Carousel Wind Tunnel, or CWT), and presents a plan for implementing the proposed research program.

Introduction to aeolian processes

Many processes modify planetary surfaces, including volcanism, tectonism, and impact cratering. Surface weathering and erosion, as by aeolian or wind activity, are particularly important on planets having atmospheres. Thus, any planet or satellite having a dynamic atmosphere and a solid surface may be subject to aeolian processes. A survey of the Solar System (Table 1) shows that Earth, Mars, and Venus meet these criteria.

Table 3.1 Relevant properties of planetary objects potentially subject to aeolian processes

	Venus	**Earth**	**Mars**
Surface gravity (Earth = 1)	0.88	1	0.38
Surface gravity (cm s^{-2})	890	981	371
Atmosphere (main components)	CO_2	N_2,O_2	CO_2
Atmospheric pressure at surface (millibars)	90,000	1,000	7.5
Mean temperature at surface (°C)	480	22	-23

Wind has the potential for directly eroding material and redistributing it to other areas. Wind transports sediment via: *suspension* (mostly silt and clay particles, i.e., ≤ 60 μm), *saltation* (mostly sand size particles, 60 to 2000 μm in diameter), and *surface creep* (particles ≥ 2000 μm in diameter). Wind "threshold" curves derived from laboratory experiments (Fig. 3.1) define the minimum wind friction speed (Bagnold, 1941) to initiate movement of particles in different planetary environments. The ability of wind to attain threshold is primarily a function of particle characteristics (size, shape, density, etc.) and the properties of the atmosphere (density, viscosity, etc.). Thus, the low density atmosphere on Mars requires relatively high wind speeds to move particles, whereas relatively gentle winds can produce the same result on Venus.

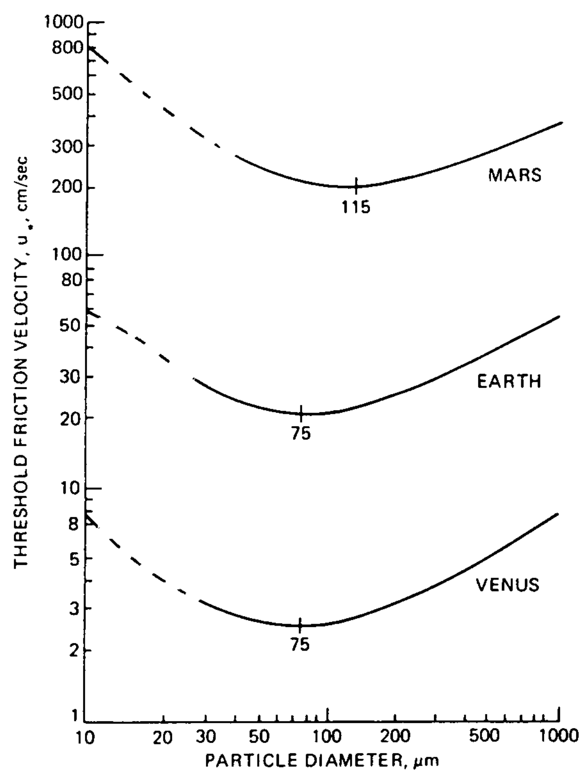

Figure 3.1: Comparison of threshold friction speed versus particle diameter for Mars, Earth, and Venus. The friction velocity is a function of the wind velocity profile above the surface; dashed lines are extrapolated (from Greeley and Iversen, 1985).

Aeolian processes are capable of redistributing enormous quantities of sediment over planetary surfaces, resulting in the formation of various landforms and deposition of windblown sediments that can be hundreds of meters thick. Any process capable of bringing about these changes is relevant to the geological evolution of the planet. Furthermore, because aeolian processes involve the interaction of the atmosphere and lithosphere, knowledge of aeolian activity leads to a better understanding of planetary meteorology and climate history. For example, the paucity of impact craters on the vast north-polar dunes of Mars would indicate the relative youth of the dunes; if the dunes presently are inactive, then they might reflect a recent change in climate, i.e., a decrease in winds of sufficient strength for sand movement and dune formation.

It is estimated for Earth that more than 500 x 10^6 metric tons of dust are transported annually by the wind (Peterson and Junge, 1971). Dust storms also reduce visibility on highways and are responsible for loss of life and property. Atmospheric dust, whether raised by winds or injected into the atmosphere by volcanic processes, also can have a significant effect on atmospheric temperature, as demonstrated on Mars via Mariner 9. Thus, windborne particles can have a direct effect on the climate. In addition, windblown sands cause abrasion and erosion of natural and manufactured objects, and encroach upon cultivated areas, turning productive land to desert, a process termed *desertification*. The problem of desertification is enormous and is recognized on all inhabited continents of Earth. Agricultural land damaged by wind erosion in the United States alone varies from 400 to 6,000 km^2 per year.

Great quantities of silt and clay are transported in dust storms and eventually deposited (Goudie, 1983). Dust deposits are difficult to identify by remote sensing; yet, identification of such deposits is very important in interpreting some planetary surfaces. For example, substantial areas of Mars may be mantled by aeolian sediments and the analysis of Viking data and remote sensing measurements anticipated from the Mars Observer mission require detailed knowledge on the erosion, transportation, and deposition of particles by the wind.

Observations of active aeolian features provide direct information on atmospheric processes. Crater-related streaks on Mars are albedo patterns that show local surface wind directions. Repetitive imaging of crater-streaks shows that many of them appear, disappear, or change their position with time. Mapping the orientations of these features has been used to assess empirically the patterns of near-surface wind circulation (Thomas et al., 1981; and others). Knowing the details of how and why crater streaks form would provide additional insight into local meteorological conditions on Mars.

Although many advances have been made in the study of aeolian processes in the last decade, knowledge of how "dust" (particles ≤ 20 µm) becomes airborne remains enigmatic, especially for martian dust storms. The "threshold" curve (Fig. 3.1) shows that particles ≤ 80 µm in diameter become increasingly more difficult to move by the wind as particle size decreases. The main cause results from various interparticle forces (electrostatic charges, cohesion from moisture, etc.) which become increasingly important as particle size decreases (i.e., the ratio of surface area-to-mass increases, making surface effects more dominant).

From a "first-principles" perspective, particle movement will occur when the effects of aerodynamic lift (L), wind drag (D), and moment (M) exceed the particle weight (W) and interparticle force (Ip), as shown in Figure 3.2. For sand-size and larger grains (>60 μm), the Ip term is relatively unimportant and existing theory for the movement of large

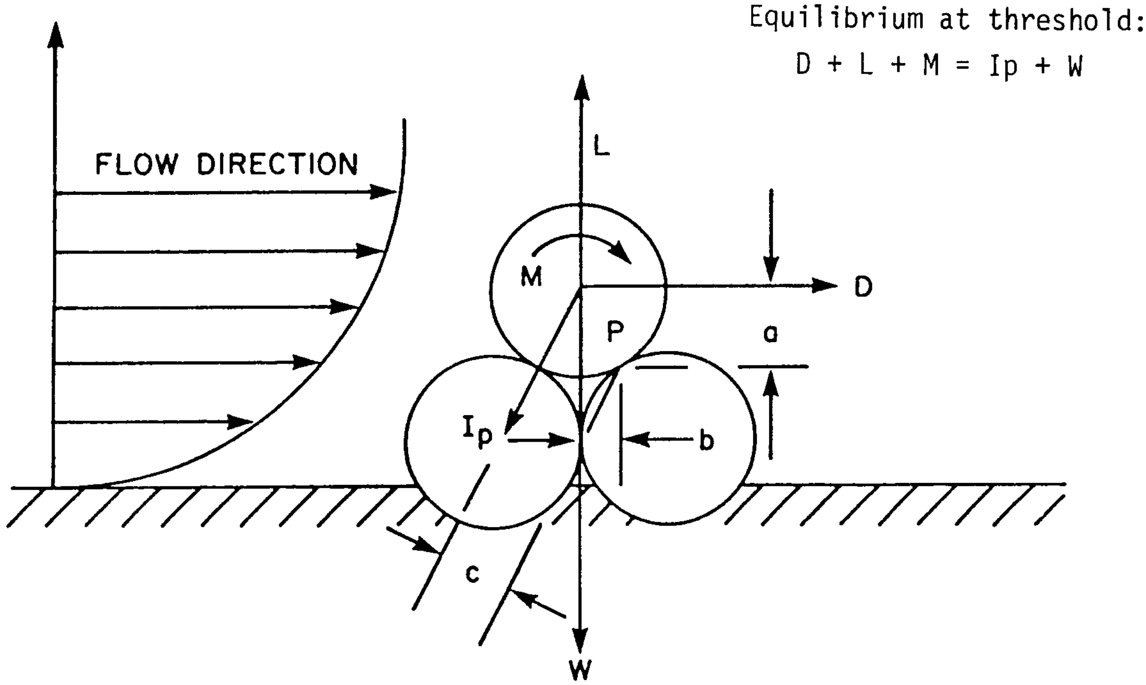

Figure 3.2. Diagram showing stylized wind velocity profile and the forces acting on a particle at rest; L = aerodynamic lift, D = wind drag, M = moment, W = particle weight, and Ip = interparticle force.

grains appears to be valid. Very few experiments, however, have been conducted with dust-size (≤ 20 μm) grains, nor has theory been developed because the problem is very complex. Dust particles a few microns in diameter are well beyond the "understood" range of the threshold curve (Fig. 3.1). Yet, it is this size of particle that constitutes dust storms and deposits on Earth and Mars.

The principal cause for the lack of knowledge on the physics of windblown dust is the unresolved interparticle force term. In effect, it is difficult to separate the weight (W) term from the interparticle force (Ip) term for experiments conducted on Earth, making the study of various Ip forces virtually impossible. However, in a weightless environment the "W" term is effectively removed in the equation, leaving only the interparticle force term. ***Consequently, one of the primary objectives of the proposed Space Station experiments is to study threshold conditions in the absence of gravity in***

order to study interparticle forces. Moreover, these and related experiments bear directly on other processes involving particles, including granular flow and solar nebula formation.

Approach for the study of aeolian processes

Aeolian processes incorporate elements of geology, meteorology, physics, and chemistry. A unified study, therefore, requires a multi-disciplinary approach using results from field studies on Earth, numerical analyses, laboratory simulations, and interpretation of spacecraft data. The *Planetary Aeolian Consortium* (Table 3.1) has used this approach to study aeolian processes on Earth, Mars, and Venus. Use of wind tunnels to investigate the physics of windblown grains under a wide range of planetary atmospheric conditions has provided critical information on the movement of particles by the wind, formation of sedimentary structures, and patterns of erosion and deposition associated with various landforms. The results from these studies not only have provided insight into the surface evolution of Mars (and Venus), but to Earth as well. Through this work, the consortium has established an international reputation for study of aeolian processes, particularly through the use of wind tunnels and other laboratory simulations.

Table 3.2 Planetary Aeolian Consortium

Investigator	Affiliation	Specialty
Greeley, R.	Arizona State University	Principal Investigator and Planetary Geologist
* Gillette, D.	NOAA	Meteorologist
Iversen, J.	Iowa State University	Aeronautical Engineer
+ Krinsley, D.	Arizona State University	Geologist
Leach, R.	ASU/Ames Research Center	Aeronautical Engineer
Marshall, J.	ASU/Ames Research Center	Geologist
* Nickling, W.	University of Guelph, Canada	Soil Physicist
Pollack, J.	Ames Reseach Center	Planetary Physicist
* Sorensen, M.	Aarhus University, Denmark	Statistician
Tsoar, H.	Ben-Gurion University, Israel	Geologist
+ Ward, W.	U.S. Geological Survey	Planetary Geologist
White, B.	Univ. of California/Davis	Mechanical Engineer
* Willetts, B.	University of Aberdeen, U.K.	Engineer

+ Not presently active in consortium
* Potential Space Station experimenter

In summary, aeolian processes play a significant role in the modification of the surfaces of Earth and Mars; some evidence suggests that Venus also may experience aeolian activity. Dust storms constitute a particularly important aspect of aeolian processes, both on Earth and on Mars. Yet, many of the fundamental aspects of dust movement by the wind remain unknown, primarily due to lack of knowledge of the interparticle force term in the threshold equation. The potential for conducting experiments on the Space Station under reduced gravity conditions, or in the absence of gravity, would enable the study of various interparticle forces which, in turn, would shed light on the very essence of the dust transport phenomenon.

3.2 Scientific Rationale

Introduction

The key to understanding problems associated with aeolian sediments is knowledge of the physics of windblown particles. Many parameters, such as grain size and wind speed, must be considered in assessing the entrainment and transportation of windblown grains. Beginning with research in the 1920s, numerous investigators have used wind tunnels to analyze particle entrainment. Wind tunnels have the advantage that individual parameters can be closely controlled and isolated for study.

Many aspects of aeolian processes have been investigated by the Planetary Aeolian Consortium, including particle threshold using both wind tunnels and theory (Greeley and Iversen, 1985; Greeley and Leach, 1978; Greeley and Marshall, 1985; Greeley et al., 1976, 1980a, 1983, 1984; Iversen and White 1982; Iversen et al., 1976a,b,c, 1986; Nickling, 1984; Nickling and Ecclestone, 1980, 1981; Pollack et al., 1976). Trajectories of individual particles in saltation have also been analyzed (White and Schulz, 1977; White et al., 1975), as have the mass sediment transport capacity of the wind (Greeley et al, 1980b; White, 1979, 1981; White et al., 1976) and the effects of erosion (Greeley et al., 1974a,b,c; Iversen and Greeley, 1984; Iversen and Jensen, 1981; Iversen et al., 1973, 1975a,b, 1976c), deposition (Iversen, 1980, 1981, 1982) and abrasion (Greeley and Iversen, 1985; Greeley et al., 1982). In these studies, the understanding of the physical processes involved in aeolian transport have been substantially advanced by varying the particle density (100 to 11300 kg/m^3), atmospheric pressure (0.005 to 35 bars) and particle diameter (40 to 10000 μm) appropriate for different planetary environments, but we have been constrained by Earth's gravity.

Gravity is one of the most critical parameters in the analysis of sediment movement; however, there are no feasible means for isolating and assessing the effect of low gravity during experiments conducted on Earth. Experiments on the Space Station not only would enable gravity to be assessed as a parameter, but through its control and elimination in some experiments, other critical parameters, such as interparticle forces, could be evaluated.

Static threshold experiments

Static threshold defines the minimum wind speed (or friction speed, u_{*t}, a parameter related to the *surface shear stress* exerted by the wind) required to initiate particle motion over a bed of stationary grains and is the fundamental parameter controlling aeolian processes. The prediction of threshold wind speed involves determination of the forces acting on the resting particles, including aerodynamic lift and drag, weight, and interparticle force. As discussed in Section 1, elimination of the particle weight term in the threshold force equation would enable a more accurate measurement of interparticle force, which is in question both in magnitude and origin. Threshold experiments conducted at one "g" indicate that the interparticle force is at least proportional to the particle diameter, as predicted by the Van der Waal's force, although the coefficient of proportionality is much smaller than the Van der Waal's coefficient for particles 30 to 100 μm in diameter. Feasibility experiments conducted in the NASA microgravity facility provide some clues to the magnitude of the interparticle force term (discussed in Section 3.3).

In addition to Van der Waal's force, other interparticle forces include cohesion due to moisture and electrostatic charges. Electrostatic charges are known to be significant in sand and dust storms on Earth (Mills, 1977) and are predicted to be important in martian aeolian processes (Greeley, 1979). The study of this and other interparticle forces as functions of wind speed and particle size, shape and composition would constitute an important aspect of experiments proposed for the facility.

The relevance of these experiments can be considered in the context of martian dust storms. Despite more than a decade of study, the mechanics for raising fine dust on Mars to form the frequent global storms remain a mystery. Because extremely high winds *appear* to be required for static threshold of grains on Mars (Fig. 3.1)--and because such winds are either absent or rare--various *ad hoc* mechanisms have been proposed for dust-raising, as reviewed recently (Greeley, 1986). These mechanisms include injection into the airstream by outgassing of CO_2 (Johnson, 1975), or H_2O (Hueginen et al., 1979), and entrainment by dust devils.

While some of these mechanisms may occur on Mars (such as the recent discovery of dust devils by Thomas and Gierasch, 1985), their relative importance in dust storm generation is at present unknown. Observations of dust storm frequency and intensity on Mars may also imply that the threshold curve for Mars, derived from wind tunnel experiments, is in error or cannot be extrapolated to consider very small particles.

The smallest particles that have been tested in a low-density atmosphere are 38 μm in diameter which is considerably larger than the particle size range (~2-3 μm) thought to exist on Mars (Pollack et al., 1977). Extrapolation of the derived curve for particle diameters more than an order of magnitude smaller is rather tenuous, particularly since interparticle forces which are not thoroughly understood are thought to increase significantly with decreasing particle size.

The steepening of the wind-tunnel-derived martian threshold curve with decreasing atmospheric pressure (Fig. 3.3) also suggests that other factors may be affecting fluid threshold that are not taken into account in this bivariate relationship. For example, it is known that the electrical conductivity of carbon dioxide is highest at approximately 6 mb pressure, which is equivalent to the average pressure on Mars. This could mean that charge transfer among particles and between particles and the surface is enhanced, possibly resulting in greater cohesion for the bed as a whole, thereby increasing the fluid threshold.

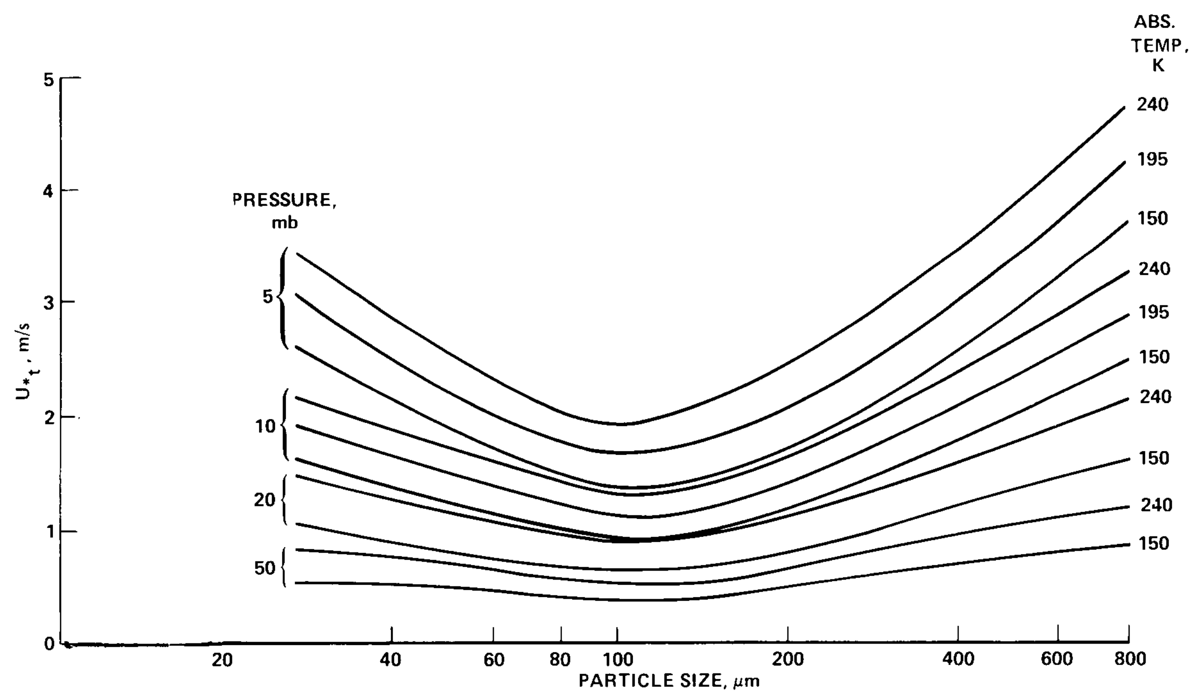

Figure 3.3. Threshold curves (wind friction velocities) for particle movement on Mars derived from experiments, showing increase in slope for winds with decrease in atmospheric pressure.

Alternatively, on Mars the higher electrical conductivity of the atmosphere could allow the charges on the grains to "leak away", and thus decrease the particle cohesion and the threshold wind speed. In the proposed Space Station experiments, these interparticle forces could be measured directly in the absence of gravity to determine their effects on threshold conditions.

The physics of saltation

The saltation process is a complex phenomenon, aspects of which are stochastic in character (Anderson and Hallett, 1986; Sorensen, 1985). The particles in motion within a saltation layer usually exhibit a large range of particle sizes, governed by some statistical distribution. The particle trajectories vary through a large range of values of trajectory height, length, and speed. The turbulence within the boundary layer is particularly important for small (dust) particles and also can be described statistically. The stochastic nature of the saltation process is primarily responsible for the problems encountered in measuring and predicting parameters such as mass transport rates.

Although the threshold process in the apparatus proposed for experiments on the Space Station closely simulates the process on Earth and Mars, the saltation dynamics are somewhat different. Particle trajectories will have a similar but somewhat different shape in the experiment apparatus from those on a planetary surface because of the absence of external gravitational attraction. However, the basic physics of the saltation process remain the same, and the opportunity to observe particle motion is much enhanced compared to Earth because, at the low values of threshold achievable in zero-gravity, the particle speeds will also be low. Thus, not only should it be possible to study the trajectories of small-particles affected by turbulence to a degree heretofore unattainable, but the stochastic nature of trajectory distribution should also become much clearer. The effects of particle impact on threshold and on particle injection during saltation at speeds above threshold are currently of much interest (Haff, 1983; Werner and Haff, 1986; and Iversen et al., 1986) and could be studied more closely than in Earth-bound wind tunnels because of much lower particle speeds.

Other applications

The wind tunnel apparatus proposed for the aeolian experiments possibly could be used for other experiments dealing with particles. For example, *granular flow* is important in many planetary processes (landslides, ash-flow emplacement, etc.) and insight into such flows could be gained via low-g experiments. In addition, some aspects of solar nebula formation involving particle interaction should be assessed in a turbulent gas flow, low-gravity environment, as would be afforded in the proposed apparatus.

Granular flow. The flow of granular material is important in many fields, including geology, industry and agriculture. The word "flow" is used for all rapid movement of granular materials characterized by high shear rates. The least complicated case is the flow of identical spherical grains with no interparticle forces and a negligible interstitial fluid. Research on granular flow began with the study of granular static deformation by Coulomb (1776) and Reynolds (1885). The flow of very dilute dispersions of particles which do not interact with each other was studied by Einstein (1906). R.A. Bagnold (1941) studied the flow of interacting particles.

There has been a rapid expansion of study of granular flow over the past decade. Modern models include: (1) continuum mechanics models based upon the theory of mixtures (e.g., Goodman and Cowin, 1971), (2) kinetic theory of gases models in which the grains are treated as analogous to the molecules of a dense gas (Ogawa, 1978). Extensions of this type of model are currently receiving considerable theoretical attention, (3) discrete particle simulations using the computer to follow individual particles (e.g., Cundall and Strack, 1979), and (4) turbulence models in which the fluctuating velocities of the grains are treated as the fluctuating fluid velocities of a turbulent flow (Jenkins and Savage, 1981).

In all these models, the value and direction of the gravitational acceleration are important factors. Experiments have been performed in which the direction of g varied with respect to the granular flow, as for example, those cases involving variable slope. The value of g has been changed for low strain-rate testing, such as in the high-g centrifuge testing of Earth structures. Bagnold's (1954) work, "Experiments on a Gravity-Free Dispersion of Large Solid Spheres in a Newtonian Fluid Under Shear" was not actually "gravity-free" but instead used neutrally-bouyant spheres in water, all at one-g.

The work proposed here represents perhaps the first granular shear flow experimentation to be done at variable gravity. Such experiments could: (1) aid in the fundamental understanding of granular flow, (2) help validate various theoretical models, (3) have direct application to certain low-g processes such as landslides or sediment sheet flows on the Moon, and other small bodies, (4) aid in the understanding of adhesion and coagulation of flux particles undergoing shear, and (5) provide qualitative information on grain-flow mechanics and dispersive stresses at the limit of low gravity and low gas pressure.

Solar nebula formation. From the broadest perspective, the apparatus proposed for aeolian simulation could also be used for fundamental experiments in particle dynamics. Particles could be placed in a flowing atmosphere which can be at a continuous or variable rate. With appropriate scaling, this condition may be analogous to some parts of an evolving solar nebula. The existence and the importance of turbulence and mass flow within solar nebula formation models are well-documented; other, non-equilibrium particle-gas flow dynamics could be envisioned in the controlled environment offered by the experiment apparatus. These experiments could involve variations in gravity and the effects of turbulence which can be induced (and adequately compared) by differential flow in the apparatus. Wind tunnel experiments of this type may provide answers to a number of fundamental dust-gas interaction questions, some of which are:

- *What grain characteristics (size, shape, charge, composition) influence grain growth (or aggregate dispersal) in a given flowing atmosphere (e.g., O-rich, He-rich, C-rich)?*
- *Do grains aggregate in a steady mass flow turbulent-free-environment over time?*
- *At the onset of turbulence, or at particular levels of turbulence, will interparticle attractions predominate? If so, for what particle size range?*

Additional refinements may include dust-gas flow experiments with the application of an ionizing atmosphere. This could be induced in the experiment apparatus or within a given phase (a rough analogy to the latter case would be an ionized atmosphere/dust flow in the ecliptic of an evolving solar nebula). These experiments may be especially fruitful if grains with mixed characteristics (i.e., spheres and laths; clays and silica; organics and graphites) were introduced.

3.3 Carousel Wind Tunnel (CWT) Design

Introduction

Boundary-layer wind tunnels appropriate for investigations of aeolian processes typically exceed 10 m in length. Size limitations on the Space Station led to the consideration of other wind tunnels that would be compact and suitable for the proposed experiments. Based on these factors, a "carousel" wind tunnel was designed which consists of two concentric rotating drums (Figs. 3.4 and 3.5) containing the test section. Differential rates of rotation of the two drums provide a wind velocity with respect to either drum surface. Rotation of the outer drum provides a "pseudo" gravity ("pseudo" in the sense that a gravity force acts on the particle while it is resting on the outer drum surface). In order to test the concept, a model Carousel Wind Tunnel (CWT) was constructed and calibrated. Tests were run in the laboratory to assess the flow-field characteristics and on-board the NASA microgravity aircraft (KC-135) to evaluate the CWT operation in a reduced-gravity environment.

Bench-testing of the CWT

Flow field experiments were run to assess the boundary layer properties that are critical for the proposed experiments. Because CWT is a new design for wind tunnels, there is no previous, direct experience upon which to draw. However, for the more general case for turbulent flow between rotating cylinders, Taylor (1935) proposed that nearly potential (inviscid) flow should occur and noted that the boundary layer should be governed by Prandtl's mixing-length theory. In the CWT it is important that the mixing-length theory govern the boundary-layer flow adjacent to the curved surfaces, because the

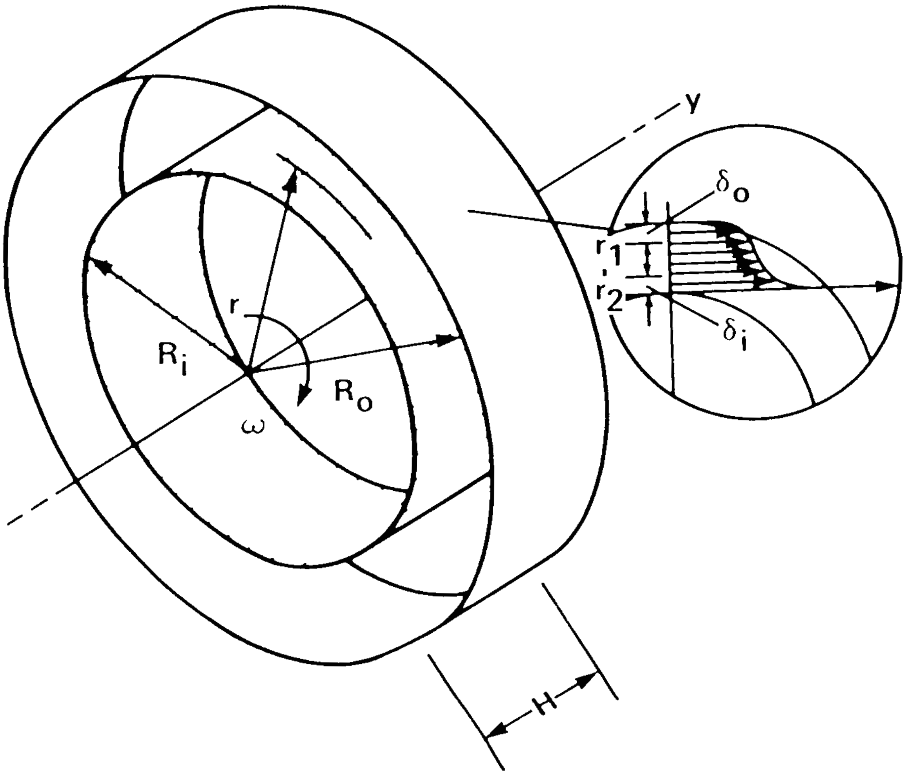

Figure 3.4. Geometry and flow characteristics of Carousel Wind Tunnel (R_i = radius of inner drum, r = radial distance from drum axis, R_o = radius of outer drum, ω = angular velocity, r_1 = radial distance to interface between the central and outer layers, r_2 = radial distance to the interface between the inner and central layers, δ_o = outer boundary layer and δ_i = inner boundary layer, H = width of apparatus.

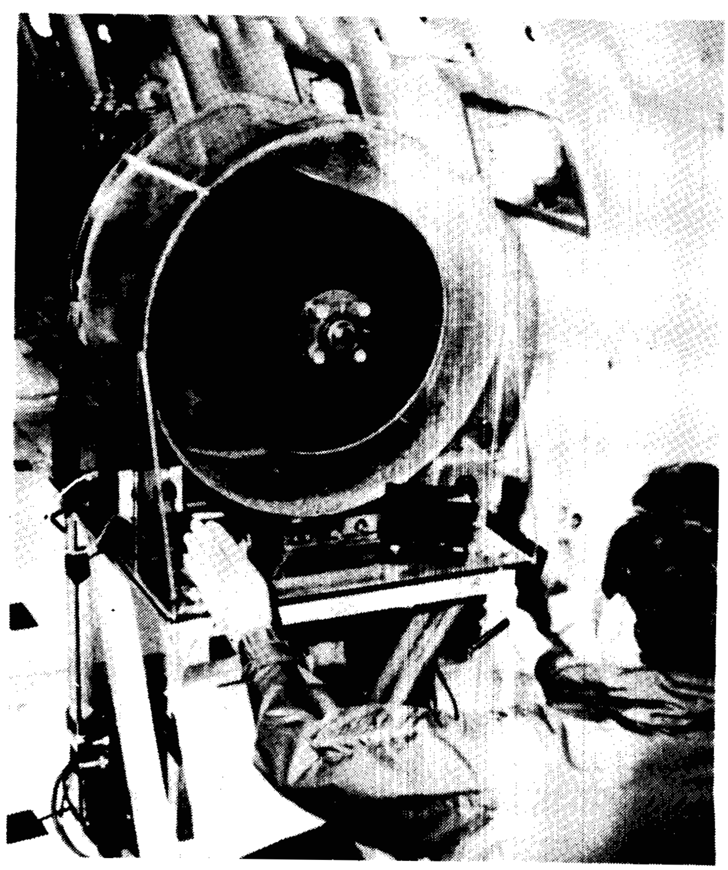

Figure 3.5. View of the model Carousel Wind Tunnel on-board the NASA KC-135 aircraft.

same theory governs the flow over a plane surface and would be comparable to natural conditions and to conditions in conventional wind tunnels. Experiments were performed in the CWT to determine if these assumptions are correct and if Taylor's hypothesis is valid. First, the following equations for the flow can be derived for an inner rotating cylinder:

inner layer (Prandtl boundary layer)

$$U = R_i\omega - u_{*i}\ \{2.5 \ln [(r - R_i)u_{*i}/\upsilon] + 5.5\}$$

$$\text{for } R_i/R_o + (\upsilon/u_{*i}R_o)e^{0.4R_i\omega/u_{*i}}$$

$$\leq r/R_o \leq r_2/R_o$$

central layer (potential inviscid layer)

$$U = KR_i\omega R_o/r$$

$$\text{for } r_2/R_o \leq r/R_o \leq r_1/R_o$$

outer layer (Prandtl boundary layer)

$$U = u_{*o}\ \{5.5 + 2.5 \ln [(1 - r/R_o)\ R_o\ u_{*o}/\upsilon]\}$$

$$\text{for } r_1/R_o \leq r/R_o$$

$$\leq 1 - 0.1108/(R_o\ u_{*o}/\upsilon)$$

in which U = the tangential wind velocity, R_i = radius of inner drum, ω = angular velocity of the drum, u_{*i} = inner layer friction speed (where the friction speed is defined as the (wall shear stress)$^{1/2}$/air density), r = radial distance from the drum axis, υ = kinematic viscosity, R_o = radius of outer drum, K = constant, r_2 = radial distance to the interface between the inner and central layers, r_1 = radial distance to the interface between the central and outer layers, and u_{*o} = outer layer friction speed.

In general, the velocity magnitude within CWT can be written as:

$$U/R_o\omega = F\{r/R_o, y/R_o, R_i/R_o, H/R_o, Z_o/R_o, R_o^2\omega/\upsilon\}$$

In this equation, y is the lateral (axial) coordinate, H is as defined in Figure 3.4, and the surface roughness of the drum is indicated by the equivalent roughness height z_o.

For general flow between two cylinders, zones of flow instability often occur in the test region. These have been investigated extensively at low Reynolds numbers ($R_o^2\omega/\upsilon$) and for low-height test sections $(R_o-R_i)/R_o$ (Coles, 1965; Fasel and Booz, 1984; Andereck et al., 1986). However, these problems may not be significant in CWT because the test section height R_o-R_i is large and the experiments are run at large Reynolds numbers.

Although preliminary experiments suggest that this assumption is valid, additional experiments need to be conducted to evaluate the flow characteristics for the full range of conditions in the anticipated experiments.

The nondimensional wind speed, $u/\omega r$, inside the CWT is a function of nondimensional radial distance r/R. The inset of Figure 3.4 represents the flow in the test section of the CWT. The wind velocity profile adjacent to the surface is representative of a turbulent boundary layer velocity profile over a smooth surface under natural conditions and in a normal wind tunnel. Experiments were conducted with CWT and turbulence intensities were measured. The results were found to be well within the range of acceptable levels for turbulent boundary layer flow in conventional wind tunnels. Experiments were conducted to assess the characteristics of the wind velocity profile (Fig. 3.6). Results show similar vertical profiles, providing further evidence that the CWT properly simulates the conventional turbulent boundary layer flow appropriate for conducting particle threshold experiments. Comparison of theoretical predictions with observed test data shows good agreement, suggesting that Taylor's hypothesis is correct and that surface friction speeds can be predicted *a priori* . There is, however, a slight discrepancy between theory and calibration at the top of the test section (near the inner drum, Fig. 3.6). This is attributed partly to secondary flows in the wind tunnel which are not taken into account in the theory. Secondary flows contain a component normal to the main flow direction and, for flows over a concave surface, can take the form of a vortex flow, called a Taylor-vortex system. To eliminate or minimize the influence of the vortex flow, anti-vortex vanes were installed in the CWT. Subsequent flow-field experiments show that the vanes greatly reduced the secondary flows. The proposed Space Station CWT is larger than the model CWT which would reduce further the secondary flows because of the larger radius of curvature.

In summary, experiments with the model CWT show that boundary layer flow is developed and is similar to flows in conventional wind tunnels that are used to investigate the physics of windblown particles. Thus, the CWT design concept appears to be valid so far as flow characteristics are concerned.

NASA microgravity facility experiments

In order to assess the performance of the CWT in a weightless environment, experiments were conducted in the NASA microgravity facility on board a specially-modified KC-135 aircraft. This plane flies on a parabolic trajectory to provide 20 to 30 seconds of low gravity; it first climbs to 10,000 m, then descends to 8,000 m, attaining an airspeed of >800 km/hr, and then climbs sharply upward at 45° to initiate the parabolic trajectory (Fig. 3.7). The radial acceleration (number of g's) of the aircraft increases to 1.8

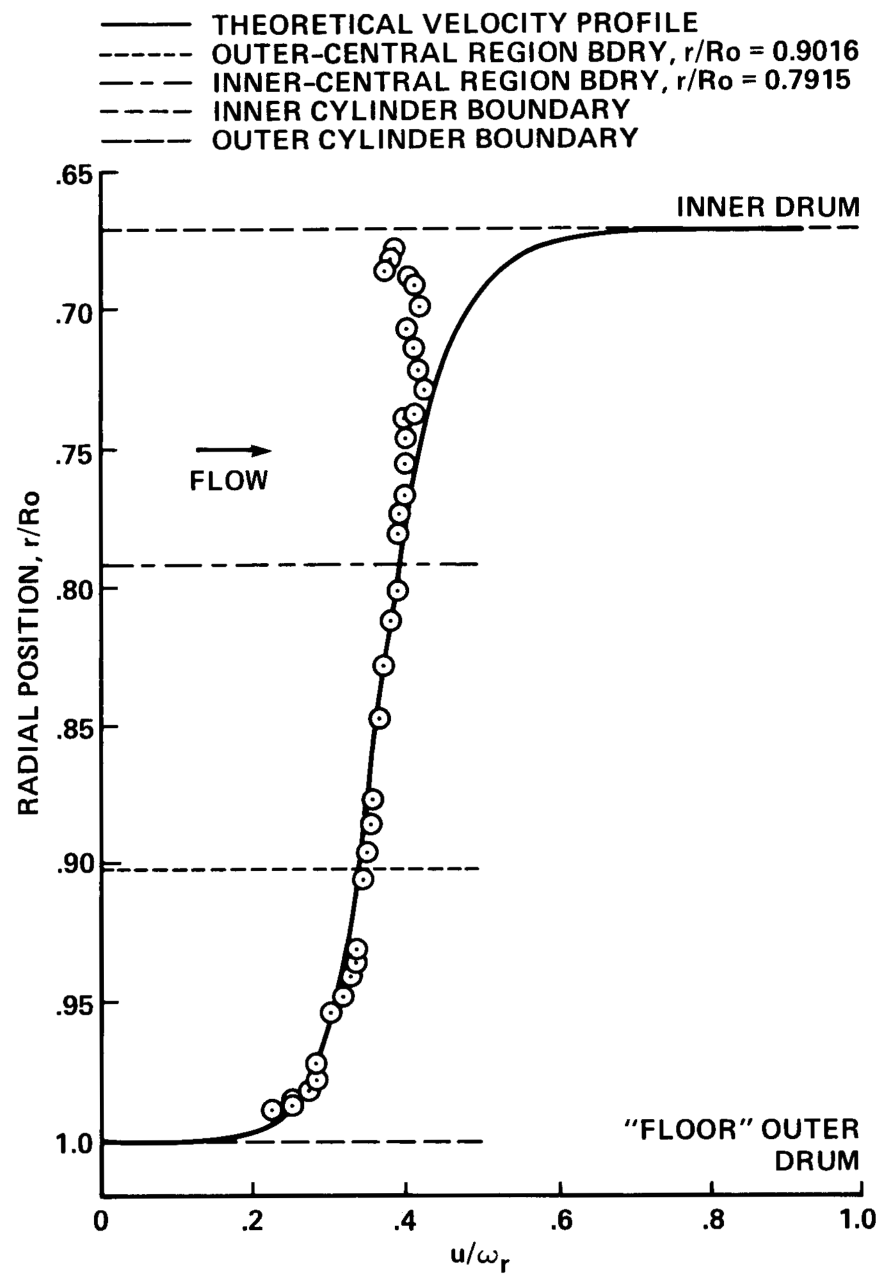

Figure 3.6. Wind velocity profile measurements (data points) made in the CWT compared with theoretical curve, showing close agreement near the floor where experiments would be conducted (R_i = 356 mm, R_o = 531 mm, ω = 515 rpm).

during the steepest part of the climb; as the aircraft pitches over the top of the trajectory, the aircraft radial acceleration decreases to a predetermined level and can be held constant (±2%) for the duration of the trajectory (Fig. 3.7). At the end of the maneuver, the sequence is repeated in a roller-coaster fashion.

Two flights have been flown with the CWT. Feasibility threshold experiments were conducted using 700 and 1080 µm in diameter particles. Particles were placed in the test section and the inner drum rotated to create airflow below threshold velocity at 1 g. The aircraft was then flown on a steadily-reducing g trajectory until particle threshold occurred. By varying the CWT airflow speed for subsequent maneuvers, data were collected for a

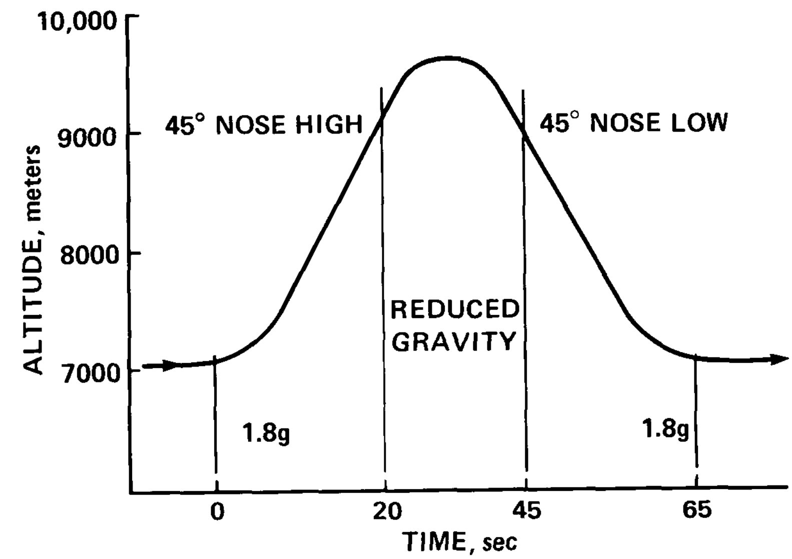

Figure 3.7. Diagram showing the flightpath of the KC-135 aircraft during a micro-gravity maneuver.

wide range of g-levels. These data are shown in Figure 3.8 along with theory as obtained from the following equation:

$$u^2{*_t} = 0.0166\, \rho_p g D_p/\rho \left[1 + \frac{0.006/2.5}{\rho_p g D_p^{2.5}}\right] \div \left[1.928 R_*^{0.092} - 1\right]$$

The data correlate well with the gravity term for values of g less than unity. The friction velocity is u_{*t} at which particle movement begins, ρ_p is particle density, g is gravity, D_p is particle diameter, ρ is atmospheric density and R_* is the friction Reynolds number, defined as $\rho D_p u_{*t}/\mu$, in which μ is the coefficient of absolute viscosity.

Figure 3.9 displays $g\rho_p D_p$ as a function of $\rho u^2{*}$. The extrapolation of these curves to $g\rho_p D_p$ equals zero and indicates the relative magnitude of the interparticle force term since equation (1) may be rewritten as:

$$\tau = \rho u^2{*_t} = f(R_{*t})\, [\rho g D_p + K I_p/D_p^2]$$

where τ is the surface shear stress, $f(R_{*t})$ is a function that depends only on R_{*t} (not I_p), and K is a constant. Thus, if g equals zero, the interparticle force may be obtained. If the interparticle force were zero, the curves in Figures 3.8 and 3.9 should go through the

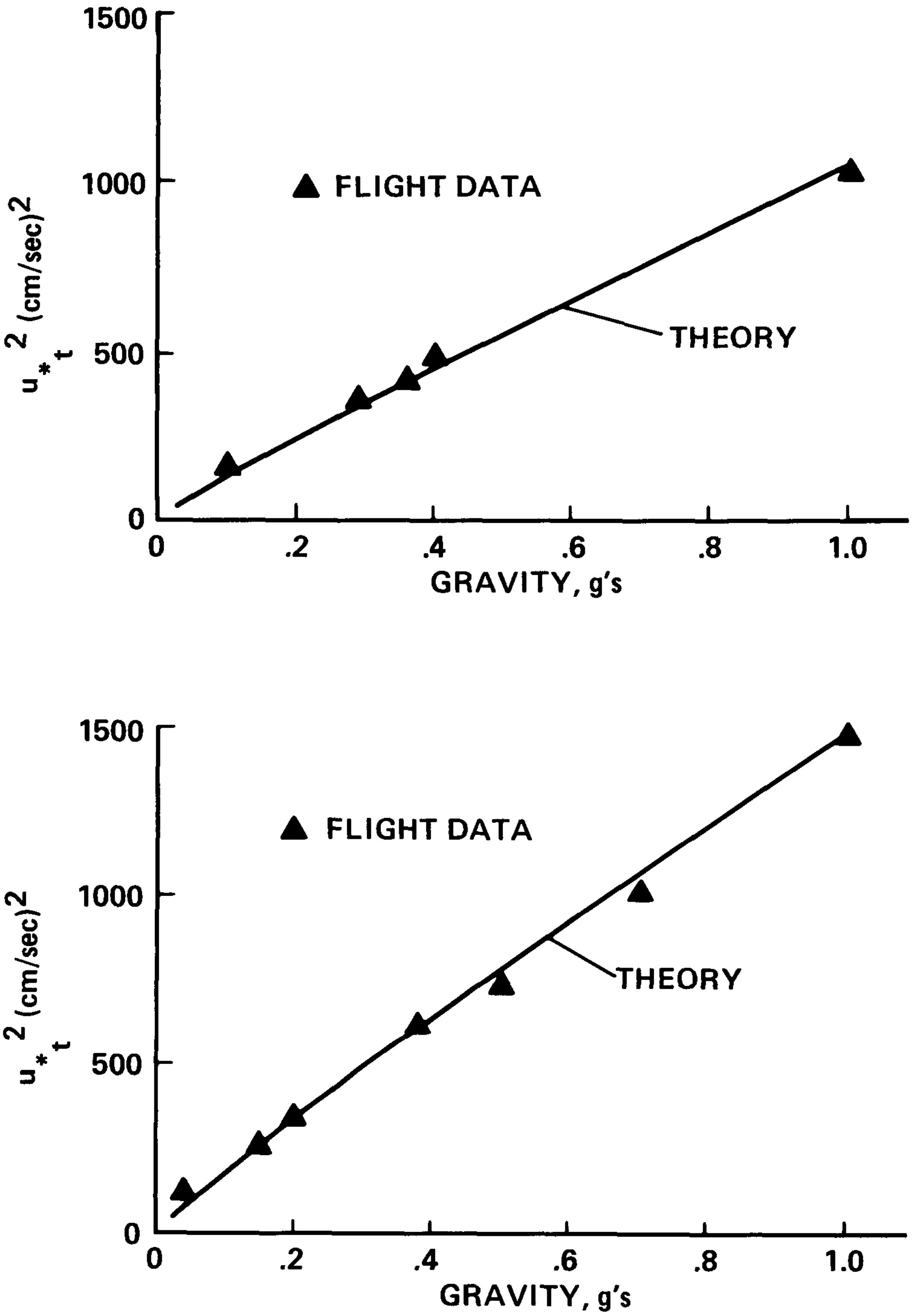

Figure 3.8. CWT experiments performed on the KC-135 aircraft showing threshold for particles as a function of gravity, for 700 μm in diameter (top) and 1080 μm in diameter (bottom) particles, compared to predictions based on theory. These results demonstrate that the CWT can be used for conducting threshold experiments.

origin. However, the curves for the 700 and 1080 micron particles are slightly above the origin showing the presence of I_p, even for these large grains. Smaller particles will magnify this effect and by cross plotting the offset versus particle size, the interparticle force as a function of particle size may be obtained.

These experiments show that the CWT can be used to investigate both gravity as a parameter in threshold experiments and the interparticle force. It must be noted, however, that the experiments conducted on the KC-135 are extremely limited and only allow testing of concepts. The very limited low- and zero-g flight duration and the high turbulence on the flights prohibit experiments with small (dust) particles, which constitute the primary experiment objectives for the Space Station.

3.4 Carousel Wind Tunnel Design for Space Station

Introduction

The Carousel Wind Tunnel and associated equipment are designed to occupy a standard double laboratory rack (~1 m wide) on the Space Station (Fig. 3.10) and to operate at a range of atmospheric pressures to simulate Earth and Mars. The operation would be automated to require minimal crew attention, other than initiation of the experiments or to repair possible malfunctions. Power would be required for several small electric motors, a video camera system and lights, and a micro-computer control system. Data would be stored on a tape medium and observations would be made via video camera for broadcast to Earth. Low atmospheric pressure in CWT for martian simulations would be accomodated via lines running outside the laboratory module and controlled through automated valves. Some particles from the experiment may be returned to Earth for analysis.

Design concepts

Artificial Gravity. Artificial gravity for threshold experiments would be obtained by rotating the outer drum of the CWT, with particles placed on the inside of the outer drum surface. For an outer drum radius of 0.5 m, the equivalent of one Earth gravity can be obtained with an angular speed of approximately 1600 rpm. For an artificial gravity of 0.1 g, the rotational rate needed is only approximately 500 rpm; thus a reasonable range of gravity values can be obtained with the CWT.

Particle handling. Test particles and cleaning materials would be stored in sealed bins located at the rear of the tunnel. Each bin would be connected to the tunnel through tubes controlled by solenoid valves, with material transferred by a pneumatic system. Loading and unloading of test particles and cleaning would be automatic from either on-board or ground command. Material from any bin can be loaded into the tunnel, transferred to another bin, or mixed together.

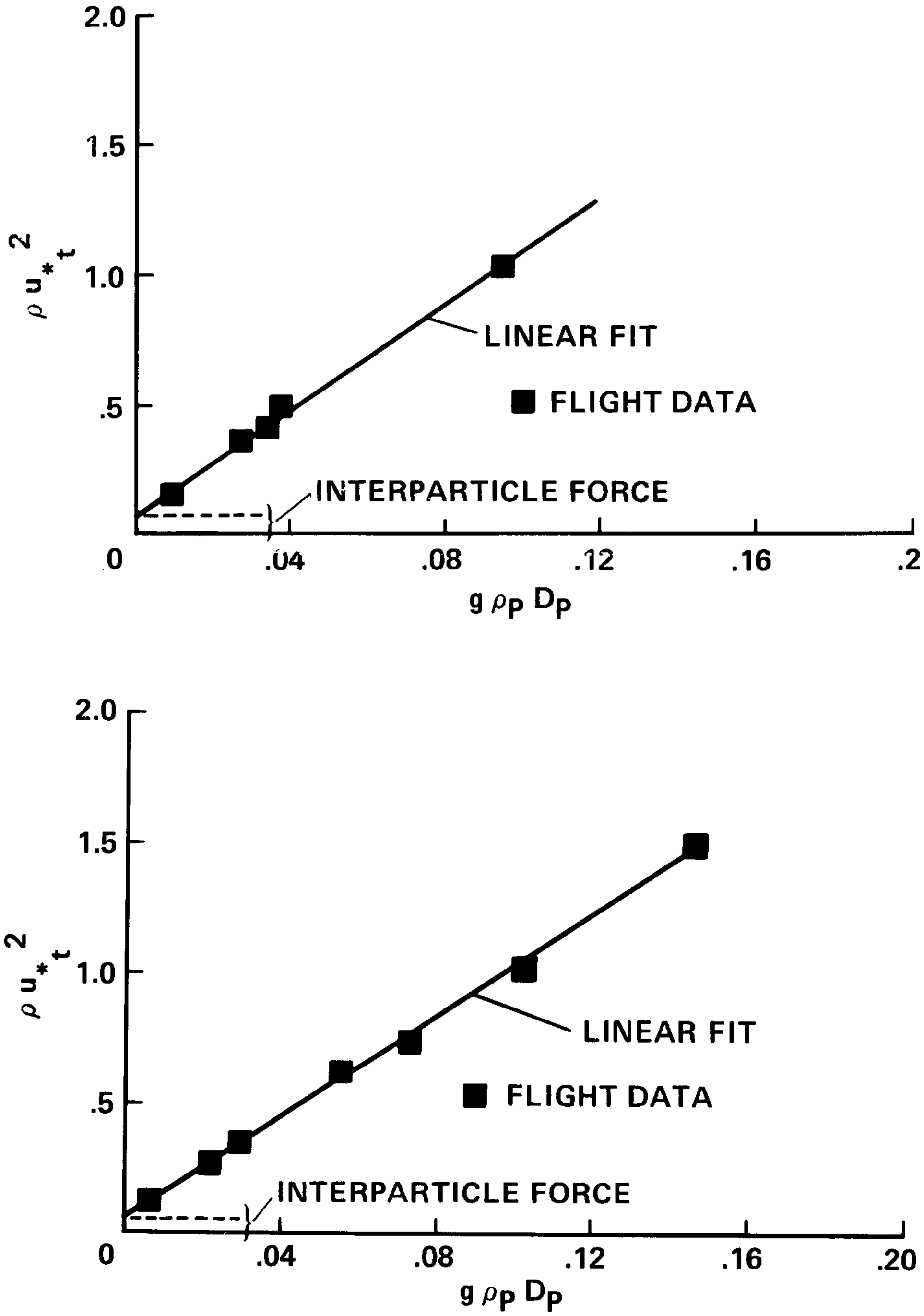

Figure 3.9. CWT experiments from 700 μm (top) and 1080 μm (bottom) particles conducted on-board the KC-135 aircraft showing linear fit through data. The curve does not pass through the zero-intercept due to the presence of interparticle forces. With decreasing particle size, the interparticle force effect is expected to increase significantly.

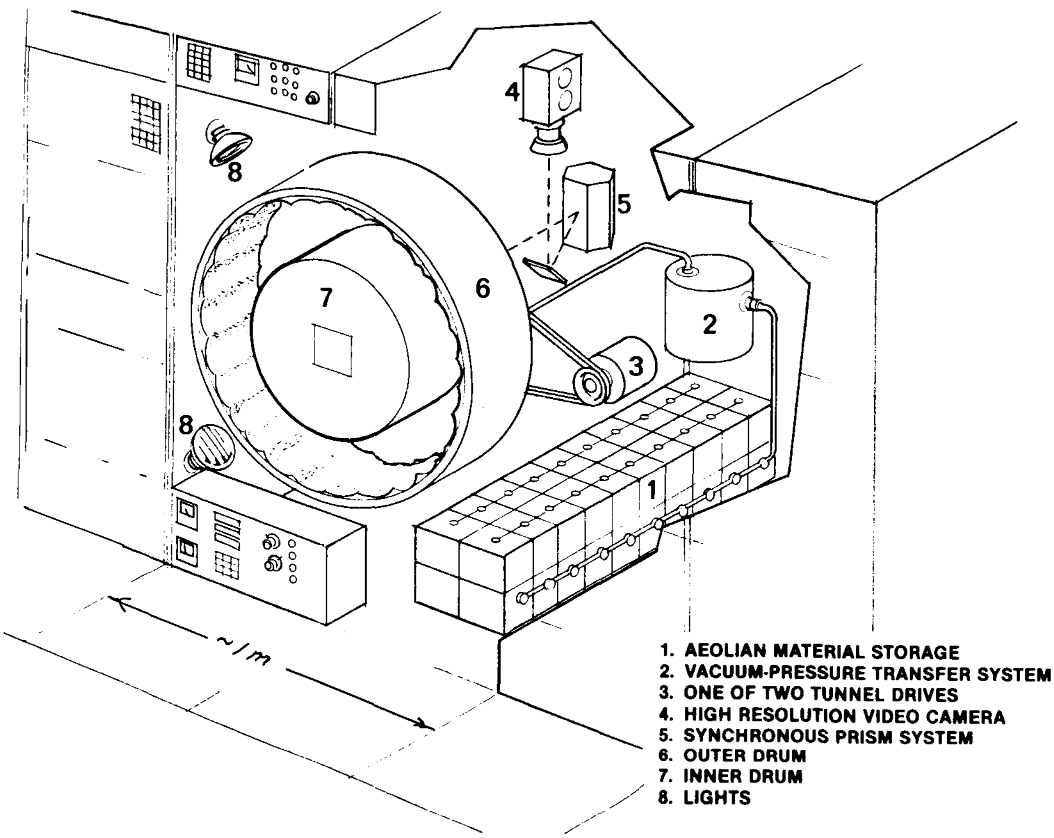

Figure 3.10. Conceptual diagram showing major components of the Carousel Wind Tunnel on-board the Space Station.

At the start of a test, particles would be injected into the test section and the inner drum rotated to distribute the particles uniformly in the test section. The threshold experiment then would be conducted, data taken using the instruments described below, and visual observations made via the video system. At the completion of the test, the particles would be automatically vacuumed from the test section. Between experiments, static charges in the CWT would be neutralized using anti-static cleaning material inserted into the tunnel in the same manner as the test particles.

Threshold detection. Determination of threshold wind speeds for particles under low gravity conditions and in the absence of gravity constitutes a key series of experiments. Threshold (initiation of particle motion) would be detected by: (1) a laser interferometer, (2) a static charge detector, and (3) a piezoelectric impact detector. The laser interferometer directs a laser beam across the test section onto photo-detectors. As the particles begin to move they interrupt the beam, causing an attenuation of the signal. A similar device currently is used (Greeley et al., 1981) and a new, more efficient device, based on the same principle but using a laser "sheet", is being developed by W. Nickling. This new design has the potential to monitor automatically the take-off velocities and sizes of particles entrained from the surface while providing a direct measure of the particle flux rate throughout the experiments.

The static charge detector consists of a pair of conductors that become electrically charged by the impact of particles. This device also has been used in conventional wind tunnels (Greeley, 1979); it can be used to detect particle motion and to monitor the level of static charge of the particles.

The third device uses a piezoelectric crystal. Particle movement is detected by the charge produced by the crystal when it is impacted by a particle. The signal from the crystal is conditioned to provide momentum information on moving particles. Three prototype instruments have been built. The first prototype measured the momentum flux of particle impacts perpendicular to the floor and parallel to the wind direction. Details of the instrument and results of saltation experiments are given by Gillette and Stockton (1986). A second instrument measures impacts on the floor and does not project into the stream of particles, thus providing a non-interfering method of measuring particle momentum flux to the floor. A third version, presently under development, is designed for outdoor experimentation and measures momentum flux parallel to the ground. It is felt that the second instrument would be suitable for use in the CWT and would provide a non-interfering, particle-movement measuring system, complementary to laser systems, that does not rely on optical methods.

Interparticle force determination. One of the most important parameters to be investigated is the interparticle force. This force is not only responsible for the high velocity winds required to initiate the movement of fine-grained materials, such as dust, but also tends to cause particle agglomeration. Because of the difficulties in working with fine particles and the measurement of interparticle forces on Earth, there is little previous experience to rely upon in the development of the experiments proposed here. However, several approaches can be explored.

First, the total interparticle force can be determined by analysis of the threshold velocity. By plotting the value of the wind-surface-friction force versus the gravitational term, the interparticle force can be determined from the non-zero y-intercept. By plotting these values for a range of particle sizes, the interparticle force can be determined as a function of particle size, as shown in the feasibility experiments flown on the KC-135. In the proposed Space Station experiments, this sequence would be repeated for particles of small size (1 to 100 μm) and of different compositions.

One of the most important parameters to be monitored and controlled is the interparticle force attributed to electrostatic charges. Operationally, electrostatic charges accumulated on the CWT drums will be neutralized between runs; however, because some of the experiments will be of long duration the particles and drums will accumulate charges during the runs. The charge would be monitored using an electrometer and could be removed if desired by generating positive and negative ions to neutralize the charges on the particles and the drum. The long-term effects of electrostatic charges could include particle agglomeration, which could alter threshold by orders of magnitude.

The interparticle force is a function of many parameters such as electrostatic charges, internal charge imbalances (as found in clay crystals), Van der Waal's forces, particle moisture content, and particle size, texture and size distributions for mixtures of grains. This will complicate the analysis of the matrix of threshold experiments to be conducted. However, by careful selection and/or preparation of the material samples, each of the major contributors to the total interparticle force may be individually identified and measured. For example, an electrically conducting material, such as copper spheres or copper powder, may be used to eliminate particle surface electrostatic charges by "grounding" the material to an electron-drainage source along the inner and outer walls of the CWT. Then, by repeating the experiment without the "grounding" effect, the influence of electrostatic surface-charges may be directly measured.

In a similar fashion, by varying test condition and test materials or properties of similar materials, the affect of internal charge imbalance, cohesive forces and Van der Waal's forces each may be measured independently and separately. For the internal charge imbalance, clays of different internal charge structure could be tested along with earth-based laboratory analysis of the internal charge imbalance (each sample) thus, directly measuring the effect of internal charge imbalance.

3.5 Proposed Plan for Development

Introduction

The research proposed here for the Space Station would be implemented by:

1. Establishment of a user group;
2. Continued testing of the CWT concept and development of a Space Station prototype, and fabrication of a flight-qualified model;
3. Instrument development and design for automation, and
4. Coordination of this program with other research in aeolian processes.

Establishment of a User Group

The research program outlined here resulted from discussions within a consortium of investigators who are engaged in the study of planetary aeolian processes (Table 3.1). The primary focus of the consortium has been on laboratory experiments (although field studies and development of theory have also been important elements) and the experiments proposed for the Space Station are a natural extension of this research to take advantage of an environment not previously accessible, but which is critically important for many aspects of aeolian processes.

Most of the investigators involved in the proposed Space Station effort (Table 3.1) already have formal and informal collaborative projects. We envision a more formal CWT user group to be formed as part of the program development. As the concepts and experiments evolve, the composition of the user group may change, especially to give new and young investigators the opportunity to conduct experiments.

KC-135 microgravity program

Preliminary experiments conducted on the KC-135 aircraft have been invaluable in testing the CWT concept and have already produced new scientific results, as discussed in Section 3. Experiments with the model CWT would continue to help refine techniques, to assess problems in particle handling, and to aid in defining areas for automation.

The next phase in the development of the research program would be the fabrication of a prototype CWT that would be a full-size model proposed for the Space Station to allow 1:1 testing of various components. As instruments and techniques for automation are developed, they would be tested using the prototype, both on the ground and on the KC-135 aircraft. As with the current CWT, "science" results can be anticipated from some of the experiments conducted with the prototype model.

Instrument development

Development of instruments and techniques for automation are key elements in the research program. The complexity of instrument development ranges from relatively simple adaptation of existing items (such as the laser threshold detection system) to the development of entirely new concepts.

Because crew time would be extremely limited on the Space Station, we would plan to automate as much of the apparatus as is reasonable and cost-effective. Although at this stage of the study, relatively little attention has been given to this issue, we consider that many aspects of the experiment could be automated.

Testing of instruments and automation procedures would be carried out both in the laboratory and on the KC-135 aircraft.

Space Station CWT

Experiments with the prototype would enable the design of the final CWT and the last phase of the implementation plan would be fabrication of a flight-qualified CWT. The fabrication could be by an aerospace company, NASA-Ames Research Center, or through a university. NASA-Ames has provided engineering and fabrication in the past for apparatus used by the Planetary Aeolian Consortium and has experience in providing space-flight components. Similarly, a university could be responsible for some flight-qualified apparatus.

Related research activities

All of the proposed investigators have active research programs in aeolian processes. Most of the group either have wind-tunnel facilities, or access to wind tunnels as an integral part of their program. Depending upon the investigators, the terrestrial work is funded by NOAA, the Department of Agriculture, the Natural Sciences and Engineering Research Council of Canada, or the Danish Academy of Sciences, whereas the planetary studies are supported by NASA. Results from these studies would continue to provide refinement of the proposed Space Station work. In all cases the investigators recognize the potential benefits to their own research through experiments that could be flown in the new environment afforded by the Space Station.

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4.0 PARTICLE FORMATION AND INTERACTION

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4.1 Introduction

A wide variety of experiments that involve the physics of small particles (µm to cm in size) of planetary significance can be conducted on the Space Station. Processes of interest include nucleation and condensation of particles from a gas, aggregation of small particles into larger ones, and low velocity collisions of particles. All of these processes could be investigated with a general-purpose facility on the Space Station for study of the physics of small particles. The microgravity environment of the Space Station would be necessary to perform many experiments, as they generally require that particles be suspended for periods substantially longer than are practical at 1-g. Only experiments relevant to planetary processes will be discussed in detail here, but it is important to stress that a particle research facility will be useful to a wide variety of scientific disciplines, and can be used to address many scientific problems. We will also discuss briefly some experiments that would not utilize such a facility. More detailed descriptions of some specific experiments are presented in the workshop abstracts.

4.2 Background and Scientific Rationale

Some of the most fundamental processes involved in the origin and evolution of the Solar System concern the condensation of solid matter from a gas, the aggregation of small particles to form larger particles, and the collisional interaction of particles over a range of sizes. Understanding particle condensation is critical to understanding the earliest stages of solar system formation. Classical nucleation theory is inadequate to predict the condensation of circumsolar grains from the early solar nebula. Experiments have been performed in terrestrial laboratories to duplicate the nucleation and condensation of planetary particles from the solar nebula, but such experiments suffer from convective instabilities induced in the gas from which the condensation takes place. In a microgravity environment, it will be possible to conduct condensation experiments with more quantitative accuracy, and to extend experiments to much more refractory materials. Experiments extended to low temperature condensation will also be able to investigate formation of icy grains that were involved in accretion of the outer planets, their satellites, and comets.

Once grains formed by condensation in the early solar nebula, they underwent aggregation into planetesimals. This process is poorly understood, particularly in the scenario where significant amounts of gas are still present. Particle aggregation is also an important part of any process that injects large amounts of comminuted material into a planetary atmosphere. Three such processes are dust storms, explosive volcanic eruptions, and large impact events. For example, it has been hypothesized that a large impact could have caused substantial atmospheric dust loading on Earth and subsequent faunal extinctions. Such hypotheses are dependent on the efficacy of dust aggregation and the rate at which particle aggregates settle from the atmosphere. Aggregation rates also play a crucial role in calculations of "nuclear winter" scenarios, and control the lifetime of some volcanic plumes and large dust storms. Some laboratory experiments suggest that aggregation, at least under some conditions, is surprisingly effective, but all aggregation experiments are severely restricted in duration by rapid settling in a 1-g gravitational field. The microgravity environment on the Space Station will allow the process of particle aggregation to be studied in great detail under a wide range of conditions. Specific parameters that need investigation include aggregation rates, the size distribution of aggregates, the dependence of aggregation efficacy on material properties, etc.

Immediately after the first stages of particle aggregation in the solar nebula, planetesimal formation probably involved collision of particles at relative velocities of a few m/sec or less. The detailed dynamics of such collisions are poorly understood, including particularly the nature of the conditions necessary for particles to adhere together after a collision. Factors that affect collision dynamics probably include particle composition, relative sizes, spin, and ambient gas pressure. The effects of all these factors are poorly known. Low velocity particle collisions also take place in planetary ring systems. Collisions result in an effective viscosity for the rings, and development of diffusional instabilities that are manifested as intricate small-scale structures. In this case the important parameter to understand is the coefficient of restitution, which describes the inelasticity of collisions. Attempts have been made to study low velocity particle collisions by suspending particles from pendula, but such experiments suffer severely from the restriction of particle motions to two dimensions. Full three-dimensional interactions, including interaction of more than two particles, can be conducted in a microgravity environment.

4.3 Hardware Concept

The high cost of experimentation on the Space Station provides a strong motivation to develop orbital laboratory facilities that will be capable of addressing as wide a range of problems as possible, rather than highly specialized facilities applicable to only one narrow problem. In principle, all of the investigations outlined above could be conducted in a chamber in which particle formation and interaction could be induced and observed. One possible concept for such a facility will be described below. A critical task to be carried out in the near term is determination of which investigations can be conducted in a general particle research facility, and which require more specialized facilities. The general objective will be to design a facility that is as flexible as possible, admitting as many high-priority investigations as are feasible without compromising the science. The design discussed here is very preliminary, and will be subjected to substantial review, refinement, and revision.

The basic facility is envisioned as residing in a glove box in one of the Space Station laboratory modules. It is felt that the glove box approach is necessary to ensure against contamination of the module interior with particles. The glove box must be at least the size of a double rack (38 inches wide) in order to accommodate the necessary equipment. It should be as voluminous as possible, and include internal power outlets and attachment to a thermal control system. The experimental chamber itself would be mounted inside the glove box. It should also be as voluminous as possible while allowing space for external attachments within the confines of the glove box; for a double rack glove box, an experiment chamber 24 inches on a side might be appropriate. All faces should be readily accessible to an experimenter outside the glove box, and the positioning of the chamber within the glove box should be adjustable. The chamber should be pressure tight, and at least one face should be completely removable. Each face should be equipped with a general-purpose port to which investigators may attach equipment. Some standard pieces of equipment should be provided as part of the facility. These might include illumination sources, still or motion picture cameras, laser nephelometers, or photometers. In the case where an investigator could not build a piece of equipment that would be compatible with a general-purpose port, the investigator could provide an entire removable face of the chamber to which his or her equipment would be attached. In the extreme case where the chamber itself is unsuitable for an investigator, it should be possible for the investigator to remove the chamber and insert a specialized one that meets his or her requirements.

The amount of crew interaction that will be required by these experiments will of course vary from one experiment to the next. In general, however, it is expected that most will require the close attention of at least one individual, either the investigator or a trained crew member. A particle research facility shares the need to effectively handle significant quantities of small particles with a number of other possible Space Station experiments, including impact experiments and a wind tunnel. This common need suggests that a standardized procedure for transporting and handling particles should be established. Equipment developed for particle transportation, handling, and storage should be as general as possible.

Several of the particle-related experiments described in the abstracts could not be accomplished in a facility within the Space Station, but could be conducted outside the Station. These include experiments to collect micrometeorites, and experiments to study the orbit properties of colliding, co-orbiting bodies. Facilities for the conduct of these experiments might be constructed outside the Space Station, or could perhaps be accommodated on free-flying spacecraft.

4.4 Recommendations

A particle research facility should be developed for the Space Station and maintained as a national facility for research involving the physics and chemistry of small particles in microgravity.

A multi-disciplinary workshop was conducted to define clearly the scientific rationale for the particle research facility, establish the desired capabilities of the facility, and establish a strawman design. This workshop was held at Ames Research Center on August 22-24, 1985. A major focus of the workshop was to establish the degree to which widely differing investigations can share the same facility, and how many specialized chambers are actually necessary.

An effort should be made to obtain funding for the facility at a level sufficient for completion at the time the Space Station reaches its Initial Operating Capability (IOC). Potential funding sources include the Astrophysics, Planetary Science, and Life Sciences programs in the Office of Space Science and Applications, as well as the Space Station Office itself.

The Space Station should be constructed in a manner that allows the development of large particle collection and interaction experiments outside the main Station structure.

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5.0 EXPERIMENTAL COSMOCHEMISTRY IN THE SPACE STATION

Al Duba (Lawrence Livermore National Laboratory).

5.1 Executive Summary and Recommendations

This report summarizes the proceedings of two workshops devoted specifically to Experimental Cosmochemistry, which were held at the Lunar and Planetary Institute, Houston, Texas, on September 12-13, 1985, and February 24-25, 1986 as part of the overall Space Station Planetary Experiments Activities (NCC 9-14 to Arizona State University and NAS-17023 to the Lunar and Planetary Institute). The purpose of these workshops was to identify and discuss experiments in cosmochemistry that cannot be conducted under the conditions available in terrestrial laboratories, but may be carried out successfully in the proposed Space Station. The scientific discussions focused on two general areas of research: 1) chemical and physical processes in the earliest history of the Solar System, and 2) general principles of magmatic processes applicable both to planetary formation and evolution, as well as present-day magmatic activity in and on terrestrial planets.

From these discussions, it was clear that the environment within the Space Station uniquely lends itself to a very broad range of experimentation that can logically follow the evolution of the Solar System from condensation-sublimation in a solar nebula, through equilibrium-evaporation and condensation in silicate, oxide, metal and sulfide systems, to magmatic processes in larger planetary bodies. The information provided in the individual summaries below shows that, whereas we cannot hope to quantify fundamentally important aspects of such processes with the experimental data-base attainable in terrestrial laboratories, a program of experimental cosmochemistry based on investigations conducted within the Space Station environment could provide these data.

Discussions also focused on possible additional projects that are not covered in this report. These might, for example, include thermochemical measurements of silicate minerals and melts with calorimetric techniques. In addition, utilization of microgravity to produce crystallographically perfect crystals for subsequent terrestrial experiments in mineral physics and experiments on trace and minor elements between minerals and melts were discussed. There are certainly additional relevant cosmochemical experiments which could be performed in the unique environment of the Space Station. Although this report does not claim to be exhaustive in terms of possible experiments that can be performed on the Space Station, it does represent a reasonable summary of the types of experiments of current interest.

The Space Station will provide a unique environment, wherein a wide range of geochemical experiments may be conducted under conditions of microgravity and high vacuum. These conditions, which cannot be duplicated in terrestrial laboratories, provide an opportunity to investigate a variety of experimental problems, ranging from vaporization-condensation of silicate, oxide, metal and sulfide systems to magmatic processes on and within small planetesimals. These experiments will lead to a better understanding of the processes that controlled the formation and chemical fractionation of the Solar System and the magmatic differentiation of planetary bodies. There is a significant overlap of interest with Microgravity Sciences which is most evident in some equipment needs. For example, acoustic levitators have the potential for measurement of physical parameters such as surface tension, viscosity, and density, as well as for containerless studies of melting, crystallization, growth, phase separation, and mixing. The molecular shields promise a stable vacuum of $\sim 10^{-12}$ Pa (10^{-17} atmospheres) with an oxygen partial pressure of $\sim 10^{-19}$ Pa in which experiments can be performed with vanishingly small chance of oxygen contamination. Participants recognized the many areas of technical overlap between experimental cosmochemistry and adjoining disciplines such as materials science, for which the theoretical and analytical basis, as well as the synthesis facilities are often identical. In line with this, the planetary program has developed instruments capable of sample characterization such as mass spectrometers and scanning electron microscopes which could be mutually beneficial to both planetary and material science principal investigators if they were part of a facility on the Space Station.

Because of the potential value of such automated analytical devices in the limited human-time environment of the Station, and because of the relatively simple nature of many of the proposed experiments, *the Workshop participants recommend that a Robot Experimental Cosmochemistry Facility be designed for the Space Station.* Such a facility might include furnaces, controllers, and temperature-recording equipment, as well as modifications of the analytical and observational equipment which is the heritage of the Solar System Exploration Division of NASA. If such a facility were automated sufficiently that a series of experiments could be conducted remotely from the ground, then it would qualify for early installation on the Space Station when crew time is likely to be at a premium. *A continuing committee composed of researchers active in the program should review the designs and studies for the facility periodically.*

We further recommend that our colleagues in the international scientific community be encouraged to participate in the Space Station. In particular, the workshop participants would welcome collaboration with either U.S. or foreign investigators in taking full advantage of the unique environmental aspects afforded by the Space Station. Such international participation was particularly beneficial to the scientific results obtained from the Apollo program. We anticipate that international scientific cooperation in the Space Station programs will be similarly beneficial.

5.2 Summary of Technical Requirements

Although the various proposed activities in this report are at stages ranging from the abstract format to projects that have already been tested in the participants' individual laboratories, it is clear each have numerous technical features in common. In most experimental plans, microgravity is the important parameter. The remaining experiments require access to high vacuums for their successful completion. For example, nearly all experimental durations range between several hours and several weeks. All experiments require temperature control. In specific instances, a furnace or the sample may require rotation in order to counteract small residual gravitational accelerations. In fact, a common denominator of nearly all of the proposed cosmochemical experiments is the very long duration during which the on-going experiment requires little or no crew interaction, but does require continuous control (through automated techniques) of the experimental parameters. The objectives of the two basic types of experiments discussed during the workshop sessions could be met using two experiment systems; additionally, these two types of experiments would benefit from an automated analytical facility. The general characteristics of these systems and facilities are:

Reduced-gravity experimental cosmochemistry

The objective is to study the processes of crystallization, melting, element distribution, and phase stability in natural materials under conditions relevant to small planetary bodies, free space, or planetary interiors. Samples are heated, at times with controlled heating rates, to temperatures as high as 1800°C under controlled atmospheres and either maintained at temperature for 10's to 100's of hours or slowly cooled at controlled rates as slow as 0.1°C/hr over several hundred degrees and then quenched. The data set for an experiment includes history of the intensive variables as a function of time, and the samples which are recovered for petrographic and chemical analysis. Terrestrial laboratory and flight design experience suggest that a typical furnace system including control electronics occupies less than 1 m^3 and requires less than 500 watts for heating and control. Although automated sample change-out would increase efficiency, several systems may be needed. Stable, low-g ($\leq 10^{-5}$) conditions are needed to minimize settling and convection during these very long experiments.

High-vacuum experimental cosmochemistry

The objective is to study the physical and chemical properties and phase stability of materials when exposed to the extreme vacuum ($< 10^{-11}$ Pa) and temperatures (300 to 2000

K) inferred for the primitive solar system. The experiment uses a wake (or molecular) shield to create very high vacuums and large pumping capacities; samples, furnaces, and monitoring equipment are contained within the cavity of the shield. Materials are heated at controlled rates (< 100°C/hr) or held at constant temperature for 10's to 100's of hours. In addition to a record of conditions as a function of time, the data set for an experiment would include in situ property measurements (such as conductivity or evolved volatiles) and recovered samples which are analyzed petrologically or chemically. A shield, 1 or 2 meters in diameter, is envisioned; experiment packages are < 0.5 m^3 and require no more than 500 watts.

Space Station automated analytical facility

There was agreement that certain standard analytical facilities should be available on the Space Station. These facilities can be shared with other groups of experiments (particularly in materials science). These include thin-sectioning, polishing facilities and ultra-microtomy to prepare experimental charges for microscopic examination, optical microscopes and scanning electron microscopy with energy dispersive spectrometry attachments, and capabilities for accurate weighing of samples (at least to 0.01 gram accuracy). For some applications, transmission electron microscopy with analytical capability as well as spectroscopic tools for surface analysis would be highly desirable. In certain important cases (volatilization experiments) a mass-spectrometric capability will add immeasurably to the attainable data base. All proposed experiments require real-time video and data communication between mission specialists and ground-based scientists during sample examination and possibly during preparation of samples for new experiments. This might take the form of a video conference which could average one or two hours per week. We note that several flight-quality analytical instruments that could be adopted for Space Station use have already been developed by the NASA Solar System Exploration Division.

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6.0 REPORT ON OTHER PROPOSALS FOR SSPEX

Joseph A. Nuth (NASA Headquarters), George Corso (Northwestern University), Donald DeVincenzi (NASA Headquarters), Al Duba (Lawrence Livermore Laboratory), John Freeman (Rice University), Ramon Lopez (Rice University), James Stephens (Jet Propulsion Laboratory), Ian Strong (Los Alamos National Laboratory), and John Wolfe (San Jose State University).

6.1 Introduction

Unlike the previous summary reports, the only unifying factor among the experiments discussed in this section is that they are all unique Opportunities and/or Techniques for High-caliber Experimental Research (OTHER!). Many of the investigations discussed in this report were submitted to the SSPEX workshops as abstracts, although several additional experiments have been added as a result of workshop discussions. Despite the enormous diversity of the proposed investigations, several common concerns have emerged regarding the availability of "standard" items.

Several people expressed a desire for one or more windows. These can be located either in the lab module, as a transparent hatch cover or in the habitability module. In general, these would not be in constant use, in fact they probably would be used only rarely. Windows should "look" both "upstream" and "downstream" from the station and should also be available for Earth and "deep space" views. Because they would be used only occasionally, positioning behind mobile equipment racks in the lab module could be considered.

Another requirement of several of the proposed investigations is the development of automated tether systems; if possible, small (< 500 m) tether systems should be able to travel along tracks spanning much of the station. Another possibility is the attachment of small tethers to one or more remote manipulator arms(s) or to one or more deployable booms. A boom which can hold a shield several hundred meters "in front of" the station (or above it) in order to avoid local contamination is a necessity for several experiments. Of course, investigators assume some astronaut EVA time for limited servicing, equipment and/or sample changes, as well as deployment or retrieval of the experiment.

One additional factor which requires thought is the degree of overlapping needs or use of common equipment for very different experiments. For example, the experiment proposed by Walker could provide a very large shield to create the ultrahigh vacuum required by Duba or Nuth (see abstracts). Could such an ultrahigh vacuum facility be useful to a larger community? Could the small tethers required by Lopez be used to deploy and retrieve Stephens' artificial comet? Could the rail gun proposed for the cratering experiments be used to fire projectiles into the atmosphere at speeds greater than 25 km/s and thus create an artificial meteor? Could the dust collectors proposed by Corso be mounted on all tethered upper atmospheric research satellites?

Along these same lines, mutual interferences among experiments with Space Station operation must be considered. As examples, could particles released by Strong or Stephens interfere with the collection efforts of Walker? How many tethers could be deployed around the station, and in which directions, before they constitute a navigational hazard? How large a disturbance to microgravity experiments would result by firing projectiles into the upper atmosphere (or doing cratering studies)?

Many of the experiments described in the abstracts are in the "formative" stage of development. Still, all of the proposals utilize the space station environment for investigations which could never be performed on Earth. None are suitable for flight on the KC-135, although several could be developed as Shuttle experiments. In some cases (e.g., Strong and Williams) development of Shuttle experiments is under way.

The following includes brief descriptions of 13 experiments; 9 of these were presented to workshop participants. Another is mentioned in the "Banks" Report as a candidate for IOC. Two more experiments were discussed by participants at the workshop, as an outgrowth of other experiments already under discussion. A final "calibration" experiment was discussed by Boynton at an earlier meeting. Considering the number and variety of Planetary Science experiments which keep emerging these should be considered as the vanguard of many more proposals.

6.2 Specific Experiments

Ultrahigh Vacuum Petrology Facility

Duba proposes placing a large (> 3 m diameter) shield in front of (or above) the Space Station. The region behind the shield would experience a very low pressure due to the shield "sweeping" ambient gas away as it travels at orbital velocity (8 km/s). Pressures of 10^{-15} torr of H and He seem possible, while atom partial pressures less than 10-20 torr could be obtained. In this very low pressure region Duba proposes to study the high temperature metamorphism of carbonaceous chondrites. In particular he proposes to measure the variation in the electrical conductivity of the sample as a function of both time and temperature in order to test the theory that the observed differences in composition of asteroids (as a function of their orbital semi-major axis) could be due to electromagnetic heating during the early history of the solar system.

Artificial Comet-Free Flyer

Stephens proposes placing several large "chunks of ice" into orbit in which finely dispersed dust particles and several radio thermometers have been frozen. The object of the experiments is to determine the dependence of the temperature structure within the comet on both the composition and concentration of the dust. In particular, he wants to test the hypothesis that a significant quantity of volatiles could be trapped inside of "dead" comets and protected by a highly efficient insulating layer of "hardened", extremely porous dust.

Artificial Comet - Tethered

In this experiment Stephens proposes to tether materials similar to those described above in order that the "comets" can be recovered for later study on earth. In this way the thickness of the insulating layer, as well as its structure could be determined and correlated with its "insulating efficiency". An additional advantage of tethered comets is observation of the development of the dust plume as a function of exposure to various levels of solar insulation.

Cosmic Dust Detector

Wolfe proposed placing a relatively large (1-2 m^2) acoustic impact detector on the space station in order to measure the long term anisotropy of the flux of cosmic dust particles. Using acoustic spectral analysis he feels that it is possible to derive some compositional information about the impacting particle as well as its directions and momentum. In this way, information about both the flux and composition of asteroidal, cometary and interstellar particles might be gained.

Cosmic Dust Collector

In this experiment, Wolfe proposes placing an electrostatic decelerator on the space station. The detector is capable of decelerating particles entering the collector with velocities as high as 25-30 km/s, and will simultaneously reject relatively slow moving debris in the vicinity of the station. Periodic return of the collector surface would allow the recovery of pristine, cosmic-dust samples which have not been contaminated by the Earth's atmosphere. Such materials would constitute an extremely valuable resource to the exobiology community.

Dust Collection using Tethered Satellites

Corso proposed outfitting satellites, which would be lowered into the Earth's upper atmosphere, with cosmic dust collectors. In this way he hopes to collect large numbers of relatively uncontaminated particles soon after their arrival. In fact, using this method it could be possible to determine to within a few hours the time of arrival of particular particles and thus correlate them with known meteor showers. Such a collection would be complementary to both the stratospheric and space station efforts.

Artificial Magnetosphere

Lopex proposes suspending a strong magnet from a tether approximately 200 m or so above the space station in order to create an artificial magnetosphere. Diagnostic probes could be suspended on mobile tethers downstream from this magnet to probe its interaction with the ambient plasma. In addition, ionic tracers such as barium could be released "upwind" at will. A series of non-tethered experiments might also be necessary to probe the effect of the tether on the plasma sheath.

Micro-gravity Petrological Studies

Williams and Lofgren have constructed a highly efficient furnace system which accurately controls the redox conditions under which the experiments are performed. They propose to fly this system aboard Space Station in order to study the effect of cooling rate on the resulting texture of chondrule-like materials. Efforts to study this problem in 1 g are frustrated by the settling of early condensates from the melt and, in some cases, by buoyancy driven convection.

Slitless UV Spectrometer (Construction and Calibration)

Wdowiak et al. have proposed the construction of a Slitless UV Spectrometer to obtain meteor spectra, and especially to determine the relative ratios of the biogenic elements in these meteors. If the cratering community (or SDI) places a rail gun (or similar facility) into orbit it might be possible to fire projectiles of known composition into the Earth's atmosphere along well determined trajectories at speeds approaching 25 km/s. Such a facility not only could be used to accurately calibrate the spectrometer but could also be used to test models of atmospheric entry phenomena.

ODACE - Orbital Determination and Capture Experiment

Walker proposed building a large dust collector (10 m x 10 m) with the capability to determine the velocity of the impacting particle. When "interesting" particles are observed the small cell (10 cm x 10 cm) containing the particle would be returned to Earth for study. At this time it might be possible to precisely determine the orbital parameters of the particle as well as a significant amount of compositional and structural information. A cosmic dust collector is mentioned in the Bank's Report as a high priority item for IOC.

High Velocity Sputtering of Amorphous Silicates

This experiment grew out of discussions with Al Duba and others at the workshop. If we put a hole in the middle of Al Duba's shield (which could be closed off, of course) then this would be an excellent source of 7-8 km/s oxygen, nitrogen, helium and hydrogen atoms with which to carry out sputtering experiments. It might also be possible to charge these atoms using an electron gun so that one could electromagnetically separate the beam into its atomic components. This device could serve as a useful experimental facility for material science experiments. In particular, Nuth wants to study the metamorphism of amorphous iron and magnesium silicates exposed to such a beam in order to better understand the processing of these materials via shocks in the interstellar medium.

Particle Release Experiments

Strong and coworkers have not yet established a definitive set of particle release experiments to be performed from the space station, in part because they have not yet carried out a planned series of releases from the space shuttle. These experiments will take advantage of the unique observational capabilities of the AMOS Facility in Hawaii in order to measure various properties of the released particles such as the scattering, absorption and extinction efficiencies as well as the speed with which the particles become aligned in the Earth's magnetic field. The results of these early shuttle experiments will determine the particular experiments which best utilize the unique opportunities afforded by the Space Station.

Calibration of Gamma and X-ray Remote Sensing Probes

Boynton mentioned this possibility at a previous meeting and it is included here for completeness. He suggests that the best place to calibrate a remote sensing tool such as a gamma-ray or x-ray fluorescence spectrometer is in the space environment. On Earth, only single-line, gamma-ray sources are available for use as excitation probes for natural samples. Similarly, no continuous "natural" x-ray spectra are available with which to calibrate x-ray fluorescence detectors. Much better instrument calibrations would be available if one could observe transported natural samples such as basalts, granites and various ices - or even observe various parts of the station itself prior to launch of the instruments to their ultimate planetary targets.

6.3 Conclusion

Since the time this report was originally compiled a number of workshops have been convened to better define experimental concepts described above. In particular, the reader is encouraged to study the report "Trajectory Determinations and Collection of Micrometeoroids on the Space Station" (LPI Report 86-05) for a discussion of potential cosmic dust experiments. The report "Experimental Cosmochemistry in the Space Station", available from Bjorn Mysen at the Carnegie Geophysical Research Laboratory in Washington, D.C., contains an excellent update and expansion of the geochemical studies discussed above as well as many experiments which were not discussed originally at this meeting. We expect that many more scientifically exciting experiments will be proposed than can actually be accommodated aboard the space station. For this reason, early discussion of potential experiments within the planetary science community is essential so that we propose only "the best" experiments possible.

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7.0 AN OVERVIEW OF THE PROGRAM TO PLACE ADVANCED AUTOMATION AND ROBOTICS ON THE SPACE STATION

Richard P. Heydorn (NASA Johnson Space Center).

7.1 Introduction

To stimulate the development of new technologies related to automation and robotics (A&R) Congress has given NASA a mandate to advance the state of art in A&R for the benefit of the Space Station and the U.S. economy as a whole. Presumably A&R developments for space could carry over, at least in concept, to terrestrial applications. Congress further stated in Public Law 98-371, July 18, 1984 that:

"The Administrator shall establish an Advanced Technology Advisory Committee in conjunction with NASA's Space Station program and that the committee shall prepare a report by April 1, 1985 identifying specific Space Station systems which advance automation and robotics technologies, not in use in existing spacecraft, and that the development of such systems shall be estimated to cost no less than 10 per centum of the total Space Station cost."

An Advanced Technology Advisory Committee, known as the ATAC, was established and did publish a two volume technical report [1] as required and, in addition, has published two subsequent progress reports [2],[3]. These reports have guided contractor studies that are currently in progress and they have been a source of information for Congress and the general public.

In addition to the ATAC, NASA also created the Automation and Robotics Panel (ARP) to conduct an independent study to provide guidance on major considerations for incorporating A&R into the Space Station design. Their findings were also published [4].

Following the ATAC and ARP studies, NASA entered into a preliminary Space Station design phase (called Phase B) to develop a conceptual design and estimate the cost of that design. As part of this effort A&R managers were appointed at each participating NASA center (JSC, MSFC, GSFC, and LeRC) to guide the Phase B contractors in developing A&R concepts for the Station. This paper will discuss some of the results of the contractor A&R effort and will also discuss NASA plans to develop a telerobotic system.

7.2 What are automation and robotics?

Before discussing automation and robotics for the Space Station, it would be helpful to distinguish these concepts from automation applications that have been employed by NASA in designing existing spacecraft. Indeed, it was the intent of Congress that NASA advance the state-of-the-art. Unfortunately, however, many of these concepts have been discussed in the engineering and computer science literature by citing specific applications rather than developing mathematical definitions of the concepts. However, Volume II of the March 1985 ATAC Report [1] offers some working definitions which are summarized here.

Artificial intelligence - This is a field of computer science dealing with inference and knowledge representation with the purpose of programming a computer to "behave" in ways that humans recognize as intelligent behavior.

Expert system - A computer program which is designed to emulate the decision-making a human expert would employ to solve a given problem.

Robotics - The study and use of machines capable of manipulation and/or mobility with some degree of autonomy.

Teleoperation - The study and use of manipulators which receive instructions from a human operator and perform some action based on those instructions at a location that is remote from the operator.

Telepresence - This describes a teleoperation situation in which the operator has sufficient cues to simulate the sensations that would be experienced in performing the operations manually, i.e., without any teleoperation device.

Automation - Use of machines which rely on artificial intelligence, robotics, or teleoperation.

7.3 Preliminary design phase studies in A&R

As part of the Phase B design studies, each of the participating contractors was asked to identify functions to be performed on Space Station that could be automated and to propose an A&R technology for implementing the automation concept. Goals such as minimize Station cost, maximize crew time savings, build in a high degree of maintainability to avoid high design risk situations, enhance safety in operating and maintaining the Station, and to the extent possible consider automation alternatives which could lead to new or advanced terrestrial applications were considered by the contractors. Initially, Space Station functions were considered individually, but as the studies progressed groupings were considered that permitted the conceptualization of generic A&R technologies. For example, generic robotic concepts were proposed that could do Station assembly, repair, maintenance, and inspection. Expert system configurations were also proposed that could coordinate and plan a number of Station activities.

In all there have been at least 400 Space Station functions that have been considered as candidate A&R applications. Table 1 lists some of the functions that could be automated through the use of expert systems or some form of robotics.

Table 7.1 Recommended Applications for the Initial Space Station

Knowledge-based (expert) systems

- Systems management-training and crew activity planning
- Space station coordinator
- Data base management-subsystem assessment, trend analysis, fault management
- Resource planning and scheduling
- Thermal curvature control
- Logistics
- Onboard personnel training
- Passive thermal monitoring
- Fault diagnosis for communication and tracking
- Power system control and management, including trend analysis and fault management
- Environmental control and life support subsystem-trend analysis, reconfiguration management, data base management, built-in testing, monitoring and recording, fault detection and identification, and assuring atmospheric integrity
- Guidance, navigation, and control-automated maneuver planning and control
- Platform applications, including power system control, distributed data processing, and planners for guidance, navigation, and control
- Laboratory module applications, including data management system and life support for experimental subject
- Experiment scheduling

Robotics

- Space station assembly
- Inspection and repair of trusses and structures
- Oru replacement
- Utility run inspection and repair
- Payload servicing -- exchange, transport, resupply, fluid transfer, and manipulation, including interfaces compatible with both robots and humans
- Laboratory functions -- care of plants and animals, analysis of biological samples, and centrifuge access

A&R was considered for the assembly, initial operating capability (IOC), and evolutionary phases of the Station. Based on constraints implied by factors such as cost or design risk, only a portion of the possible A&R will be operating by IOC. The bulk of the A&R would probably be realized in some evolutionary phase of the Station. However, to insure that this type of evolutionary development would not be too costly, contractors were asked to appropriately "hook" and "scar" the IOC design. That is, for example, they were asked to design the computer software for the data management system that could easily accommodate additional expert systems or other artificial intelligence software. Such a provision in the software is known as a "hook". Also, they were asked to have the Station be "robot friendly" by, for example, including some form labeling that could be easily recognized by a computer vision system or by including robot grappling devices that would stabilize a robot when it was performing some manipulation function. Modifying hardware in this fashion is referred to as "scarring".

7.4 Set-aside for a telerobotic system

Congress has directed NASA to set a portion of the Space Station funding aside for a flight telerobotic system (FTS). Phased over several years, the total funding of such a system is expected to be approximately 100 million dollars. The prime responsibility for its development will reside at the Goddard Space Flight Center but several of the other NASA centers will participate in the program.

It is envisioned that the FTS could perform a number of functions on the Space Station relating to assembly, maintenance, and servicing which in the absence of the telerobot would be performed manually by the crew. Characteristics of a FTS that would be needed are believed to include the following:

Mobility. The FTS could be attached to either the remote manipulator arm in the Shuttle, the mobile remote manipulator system that will travel along the truss (and is to be developed by the Canadians), the orbital maneuvering vehicle (OMV), or the service bay gantry. The OMV is a small space craft that will travel in an orbit close to that of the Space Station and be available for servicing satellites.

EVA Equivalency. The reach and strength of the FTS should be roughly equivalent to that of a suited astronaut in case the FTS fails.

Control. The FTS should be controllable from the Shuttle or the Space Station. If suitable predictive control mechanisms can be developed, it could also be controlled from the ground. The problem with control from the ground is that the operator will experience a time delay in the telemetry.

Telepresence. The operator will be able to see the object being manipulated on displays at the control station and should also have displays or some sensory feedback that will indicate the forces being applied by the system.

Evolution. The FTS will be initially designed as a teleoperation device and evolve into a device that has robotic, i.e., autonomous, capabilities.

Since the conceptual design studies for the FTS are just now being done, the specific configuration is still not known. However, it is expected that it will initially incorporate a number of features which may include multiple light sources, multiple stereoscopic cameras, and force, torque, and position sensors. To stimulate the incorporation of more advanced features at a later time, OAST is sponsoring (mainly at JPL) research into end effectors, advanced sensors, computer vision, human/machine interfaces and evolvable architectures. In addition, there are a number of contractor studies that will effect both the IOC and the evolutionary designs of the FTS.

7.5 Conclusions

The preliminary design phase of the Space Station has uncovered a large number of potential uses of A&R, most of which deal with the assembly and operation of the Station. If NASA were to vigorously push A&R concepts in the design, the Station crew would presumably be free to spend a substantial portion of time on payload activities. However, at this point NASA has taken a conservative attitude toward A&R. For example, the belief is that robotics should evolve through telerobotics and that uses of artificial intelligence should be initially used in an advisory capacity. This conservativeness is in part due to the new and untested nature of A&R; but, it is also due to emphasis placed on designing the Station to the so-called "upfront cost" without thoroughly understanding the life cycle cost. Presumably A&R has a tendency to increase the initial cost of Space Station but could substantially reduce the life cycle cost.

To insure that NASA will include some form of robotic capability, Congress directed the set-aside funding that was discussed above. While this stimulates the development of robotics, it does not necessarily stimulate uses of artificial intelligence. However, since the initial development costs of some forms of artificial intelligence, such as expert systems, are in general lower than they are for robotics one is likely to see several expert systems being used on the station.

7.6 References

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APPENDIX

ABSTRACTS OF CONTRIBUTED PAPERS

N89-15005

A PLANETARY ULTRA HYPERVELOCITY IMPACT MECHANICS AND SHOCK WAVE SCIENCE FACILITY

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Macroscopic experiments in which the amount of shock-induced melting, vaporization and ionization produced during impact of projectiles at speeds from 8 to 15 km/sec have never been conducted. Experimentation with ~10 $\bar{m}$ diameter range projectiles, have been of great value for interpreting the results of micrometeorite, cosmic and cometary dust space-flight experiments and for ground-based research on zodiacal light. The small projectile experiments have uncovered several new physical processes which could never have been discovered via only numerical calculations. Radiant energy losses from impacted regions occur so rapidly in this size regime that these affect the cratering morphology and undoubtedly chemical processes, such as incongruent vaporization and impact-induced ionization. Because impact experiments carried out with light gas gun are limited to achieving the range of shock pressures (2 Mbars) inducing melting, but not copious vaporization in silicates, there are virtually no experimental insights into such currently controversial issues in planetary science as

1. The physics of "after burn" for oblique impact on the earth and the possible formation of the moon.

2. The amount of production of very fine vaporized ejecta condensate from large impact of such as from the hypothetical K-T bolide.

3. The nature of incongruent vaporization of minerals and the possible impact devolatilization of the moon. This requires data on the speciation in the impact induced vapor.

4. The production of impact-induced vapor plumes, upon oblique impact onto various planetary targets and the possible relation of this process to sampling, via impact ejection, of different planets (e.g. Mars).

Using the concept of intercepting orbits from a pair of Space Station serviced free-flyers, a new class of impact and shock wave experiments pertinent to planetary science can be carried out. One proposed free-flying vehicle (A) is an impactor dispensor, and the second free-flyer (B) is an impact laboratory. How collision is achieved by utilizing essentially twice orbital velocity is demonstrated in Fig. 1. Vehicle A contains a series of small (1 kg) flyer plates or other projectiles which are launched into the trajectory of Vehicle B at appropriate points. Vehicle B is a large impact tank similar to those in terrestrial gun laboratories, except it contains a supply of targets and instrumentation such as high speed cameras, flash x-ray apparatus and digital recorders. As indicated in Fig. 2 shock and isentropic pressures of up to 20 Mbar are achievable with such a system which provides 15 km/sec impact velocities for precisely oriented projectiles. Future augmentation with other devices, now being developed e.g. rail guns, can, in principle, boost performance and the ability to obtain high precision data to carry out pioneering research at even higher pressures in the future.

ULTRA-HYPERVELOCITY FACILITY
Ahrens, T.J.

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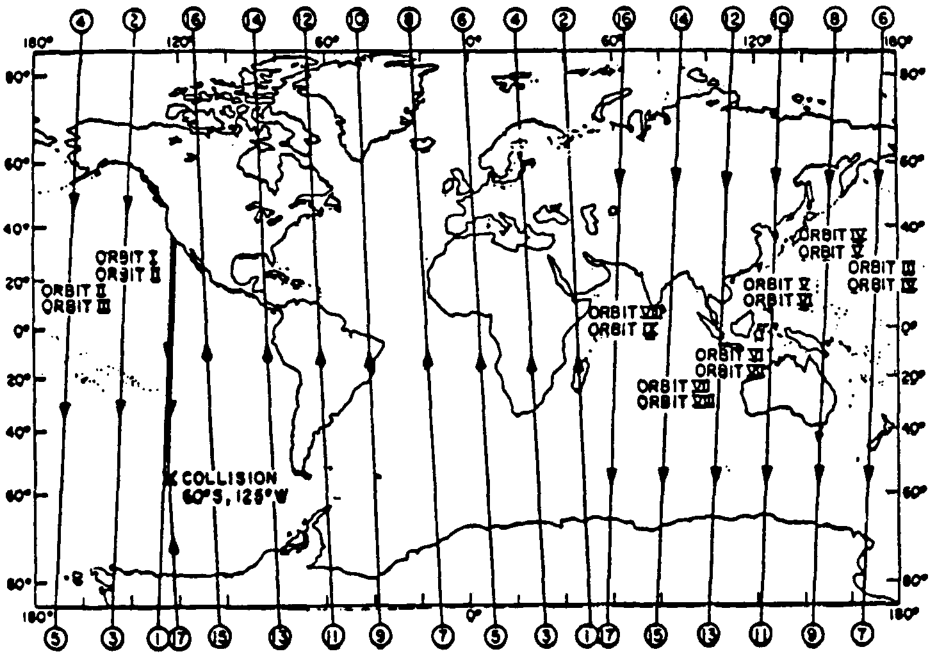
M.A. Podurets, G. V. Simakov, R. F. Trunin, L. V. Popov, and B. N. Moiseev, Compression of water by strong shock waves, Sov. Phys. JETP 35, 375-376, 1972.

Ragan, C.E., III, Silbert, M.B., and Diven, B.C, Shock compression of molybdenum to 2.0 TPa by means of a nuclear explosion, J. Appl. Phys. 48, 2860-2870, 1977.



100 naut. mi. circular orbit
Orbit period 88.2 min.
2nd vehicle launch occurs after
8.16 orbits of 1st vehicle

Fig. 1 - Ground track of vehicle launched due south from Vandenburg AFB, into 100 nautical mile elevation polar orbit, demonstrating how a second vehicle launched 8.16 orbits after first vehicle will give rise to a collision over 60°S, 125°W.

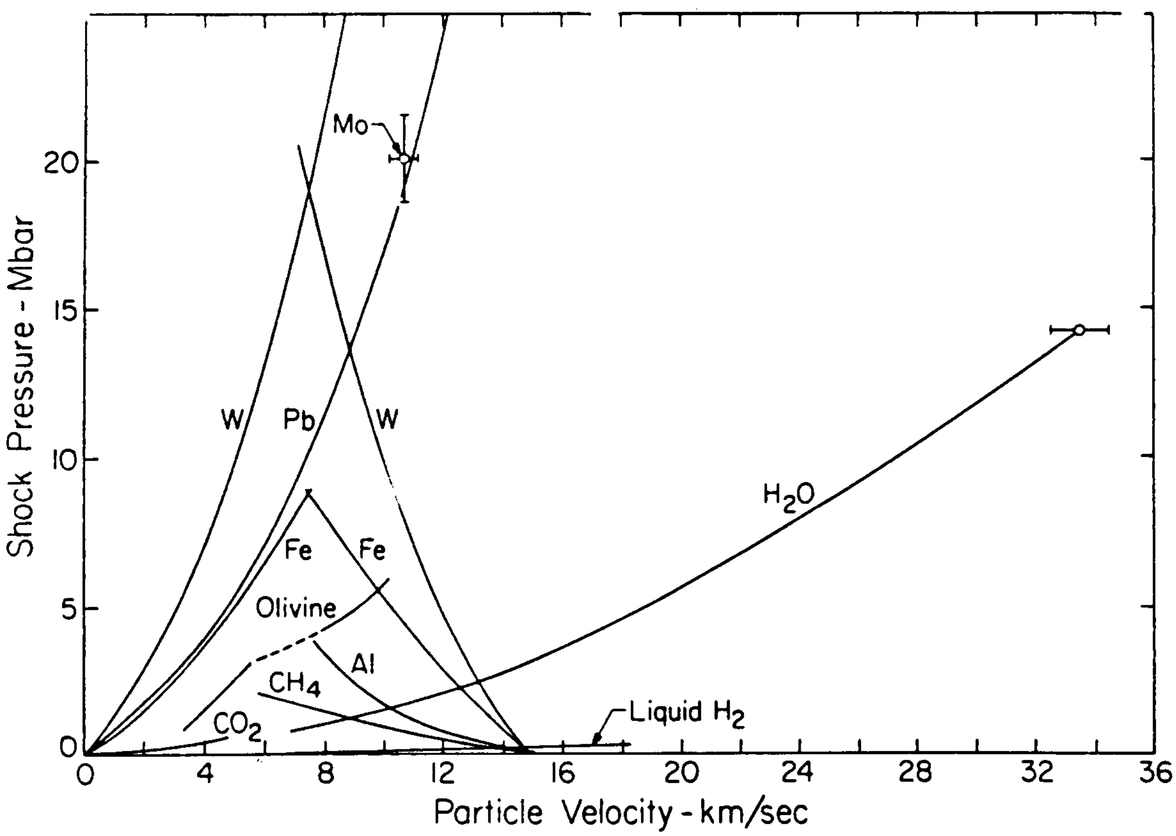


Figure 2 - Pressure-particle velocity plane for various materials, impacting at 15 km/sec. Shock pressure found by intersection of pressure-particle velocity curves, centered at 0 and 15 km/sec, e.g., ~19 Mbar for W impacting W; ~13.6 Mbar for W impacting Pb; 1.6 Mbar for Al impacting H_2O. Specific data for Mo and H_2O, with experimental errors shown, are from Ragan et al. (1977) and Podurets et al. (1972), both obtained using nuclear explosives. As can be seen from the figure, by choosing impactors and target materials a wide range of very high pressures may be achieved via a single available impact velocity.

N89-15006

PROPOSED EARTH-BASED CRATERING EXPERIMENTS AT LOW G IN HARD VACUUM

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In order to address the questions of whether the cratering scaling which has been developed by Holsapple and Schmidt (1980,1982) and Housen et al. (1983) can be extrapolated to low velocity encounters, of planetesimals appropriate for the conditions appropriate during accretion of the planets and the impact mechanics of encounters of both asteroids and the solid objects which comprise the rings of the outer major planets, a series of experiments at low g and at high vacuum are proposed. Specific issues which could be addressed include

1. What is the effect of very low g on cratering efficiency and final crater shape in unconsolidated media at low g? At what g and vacuum levels do scaling laws become affected by surface and/or electrostatic forces? Are ejecta curtains different at very low g? Could these possibly give rise to the striae seen on the surfaces of Phobos and Deimos? Is a regime achieved such that all impact ejecta escape and the projectile erodes the target and falls aways from the target?

2. What are the dynamics of impact into a strengthless spherical and ellipsoidal "liquid" targets? Is impact into a liquid sphere a viable fragmented asteroid model? What controls spall, ejecta size, mass and velocity in such a situation?

As a precursor to experiments on a space station, impact experiments employing drop towers on earth could play a useful role. Experimental facilities at NASA/Lewis and Marshall Space Centers can be employed in both developing instrumentation and obtaining preliminary impact data on geologic materials at low and very controlled g levels in hard vacuum.

Constraining likely experiments are both the size of chambers available in drop towers and their drop time. The Lewis Research Center has the world's largest such facility. It has the capability of launching a 1 meter diameter x 3.4 meter long hollow container, in which the proposed impact experiment is placed, into a vertical ballistic trajectory and thus obtain virtually zero g for ten seconds. If the container is just dropped from the top of the 145 m high tower, 5 seconds of test-time is available at various low g levels. Another facility which is a simple (100 m) drop tower is available at Marshall Center. This has a 0.9 m diameter test container. Using the formulas in Holsapple and Schmidt (1980, 1982), expected crater sizes and crater formation times were calculated for impact into Ottawa sand. Useful bounds on the crater sizes (Fig. 1) and crater formation times (Fig. 2) can be obtained by assuming the lowest and highest energy impactor which could conceivably be launched are a 0.01 g, 10 m/sec and a 1 gm, 10 km/sec plastic and iron projectile, respectively. As can be seen from Fig. 1, the 145 m tower will just barely contain the 100 cm diameter crater expected at 10^{-5} g for the 1 g - 10 km/sec projectile. Fig. 2 demonstrates that the 12 to 200 second crater formation times are much too long for the 3 to 10 second test times available from drop towers. Ejecta absorbing or catching internal walls would be required for drop tower experiments to be conducted to final crater dimensions. Moreover, although both facilities have apparatuses for decelerating payloads, because craters in unconsolidated media in vacuum are fragile, it is unlikely that good recoveries will always be obtained. Both onboard video recording and acceleration versus time recording appear to be important ingredients in obtaining high quality data in this environment.

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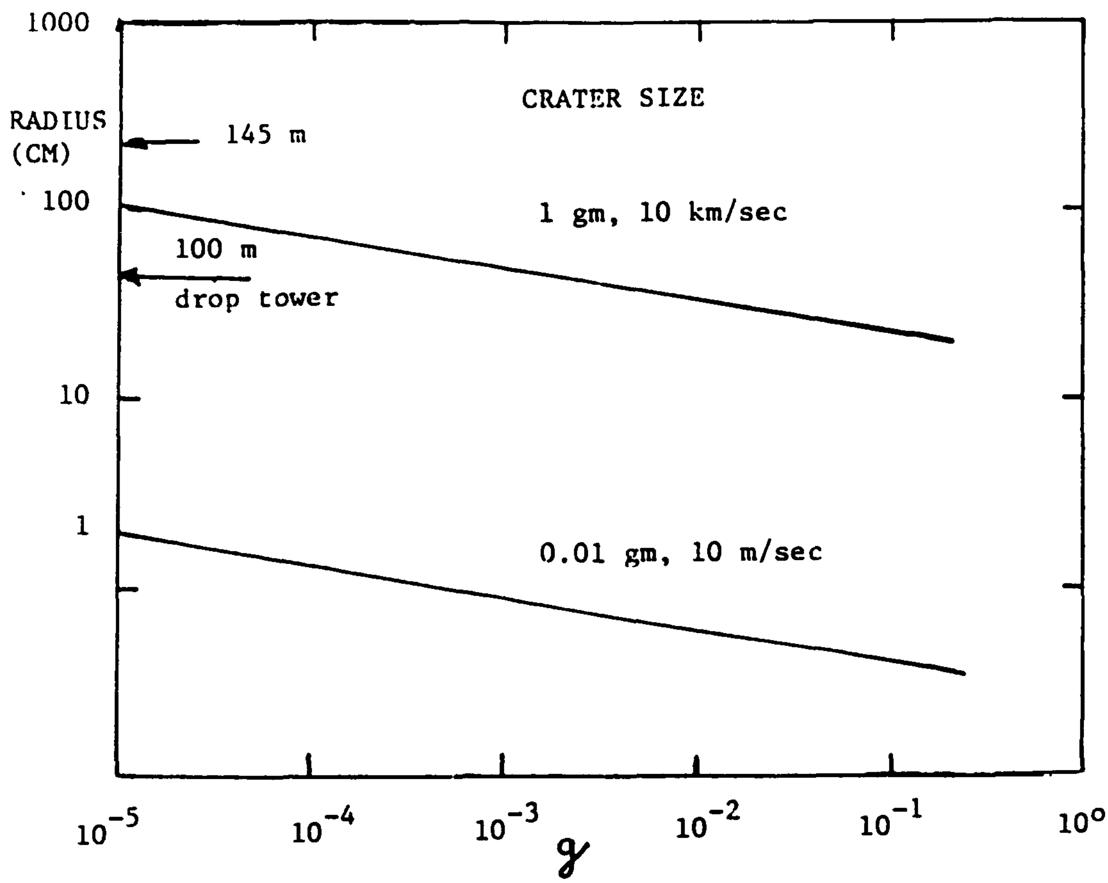

Figure 1. Calculated Ottawa sand crater diameter at different g levels for a 1 gm iron projectile impacting at 10km/sec and a 0.01 gm plastic projectile impacting at 10 m/sec. Available drop tower dimensions are indicated.

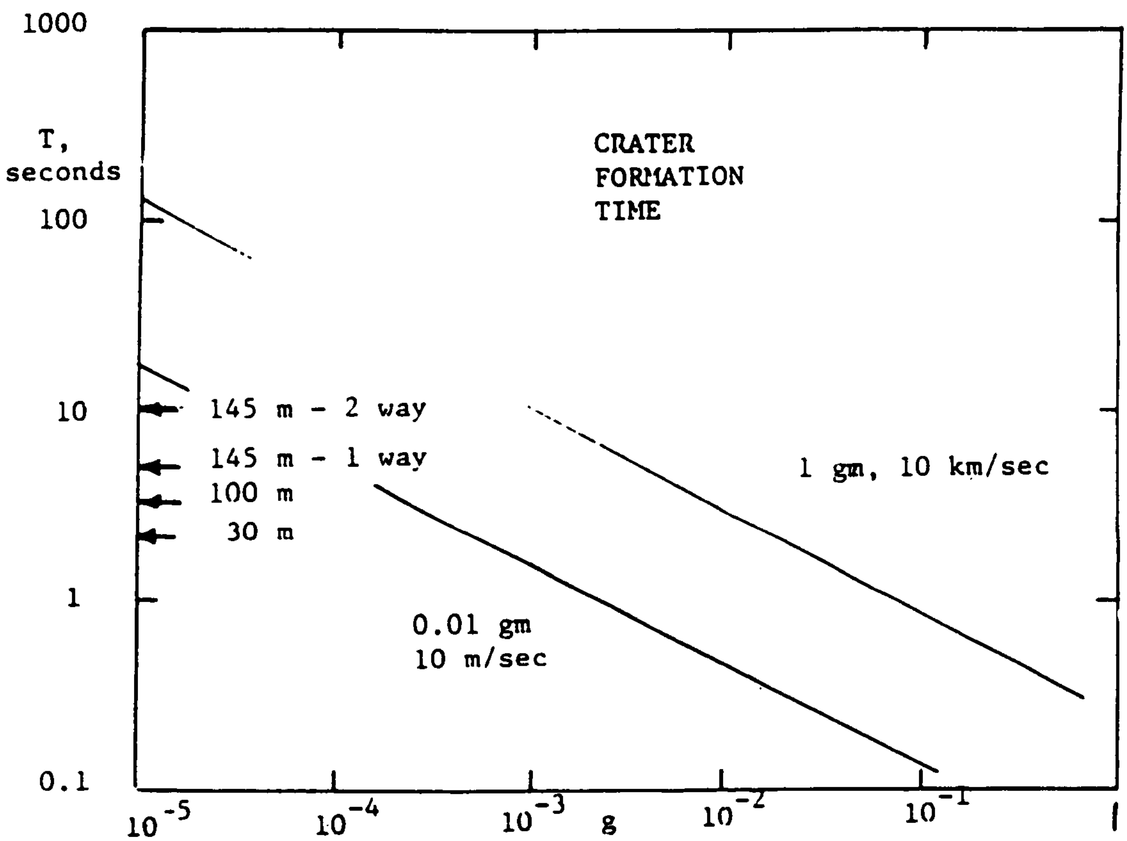

Figure 2. Calculated Ottawa sand crater formation times at different g levels for the two projectiles of Fig. 1. Drop tower test times are indicated.

N89-15007

INVESTIGATION OF THE ENHANCED SPATIAL DENSITY OF SUBMICRON LUNAR EJECTA BETWEEN L VALUES 1.2 AND 3.0 IN THE EARTH'S MAGNETOSPHERE: THEORY

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INTRODUCTION

Initial results from the measurement conducted by the dust particle experiment on the lunar orbiting satellite Lunar Explorer 35 (LE 35) have been reported by Alexander et al. (1,2,3,4) with the data interpreted as indicating that the moon is a significant source of micrometeoroids. Primary sporadic and stream meteoroids impacting the surface of the moon at hypervelocity has been proposed as the source of micron and submicron particles that leave the lunar craters with velocities sufficient to escape the moon's gravitational sphere of influence. No enhanced flux of lunar ejecta with masses greater than a nanogram was detected by LE 35 or the Lunar Orbiters (5). Hypervelocity meteoroid simulation experiments concentrating on ejecta production (6,7,8,9) combined with extensive analyses (10,11,12,13) of the orbital dynamics of micron and submicron lunar ejecta in selenocentric, cislunar and geocentric space have shown that a pulse of these lunar ejecta, with a time correlation related to the position of the moon relative to the earth, intercepts the earth's magnetopause surface (EMPs). As shown by Alexander et al. (14), a strong reason exists for expecting a significant enhancement of submicron dust particles in the region of the magnetosphere between L values of 1.2 and 3.0. This is the basis for the proposal of a series of experiments to investigate the enhancement or even trapping of submicron lunar ejecta in this region. The subsequent interaction of this mass with the upper-lower atmosphere of the earth and possible geophysical effects can then be studied.

FORMATION OF LUNAR EJECTA

An analysis of the data from the dust particle experiment on LE 35 provided the basis for the determination of some of the parameters of lunar ejecta escaping the surface of the moon (1,2,3,4). The primary reason for this interpretation resulted from a significant change in the event rate detected by the experiment during periods associated with the passage of the earth-moon system through the major annual meteor streams. This feature of the data occurred for five consecutive years. The event rate during non-meteor shower periods was essentially the same as the interplanetary rates. An additional fact was no enhancement of the event rate for nanogram size lunar ejecta which is consistent with the measurements reported by Gurtler and Grew (5).

Hypervelocity meteoroid simulation experiments (6,7,8,9) have provided ratios relating the mass of the impacting particle to the mass of ejecta produced. In order to discover the ratio, the effects of particle density as well as impact angle of incidence have been examined. Schneider (7) has found that a 10 mg particle with a velocity of 4 km/s impacting at normal incidence would produce ejecta which represented 7.5 x 10^{-5} the mass of the incident particle and had a velocity greater than 3 km/s. Alexander (8) has shown that under similar initial conditions the ejecta mass ratio, e, would be higher by an order of magnitude ($e = 5. \times 10^{-4}$). A recent study by Zook et al. (24) reported that oblique angle impacts would produce 200 to 300 times more microcraters (diameters = 7 μm) on ejecta measuring plates than would be produced by normal incidence impacts. Given that 7μm diameter microcraters correspond to particles with $m = 10^{-12}$ g (14) and that the impact velocity was 6.7 km/s, one may infer that the fraction of ejecta mass with lunar escape velocity would also increase by 200 to 300 times ($e = 1.5 \times 10^{-2}$). These three values for the "ejecta to incident particle mass" ratios will be employed to establish the total lunar ejecta mass after the interplanetary flux at 1 AU has been determined (15).

Three recent dust flux models are used for the basic calculations that are reported in this paper. The first was given by McDonnell (16) then updated by McDonnell et al. (17). The second one is that of Grun et al.(18), followed by the flux curve derived from lunar crater data as presented by Morrison and Zinner (19). The Log of cumulative flux versus the Log of particle mass for each model is depicted in Fig. 1 (20). McDonnell (17) model is based on the relevant flux measurements in the vicinity of 1 AU heliocentric distance corrected for Earth shadowing and reduced to a flat surface exposure geometry. The curve in Fig. 1 labeled Grun, reported as Model 1 (18), is a lunar flux model. The first two curves in Fig. 1 are based primarily on in-situ measurements in space and are seen to be quite similar for cumulative masses > 10^{-12} g. The most pronounced similarity which can be observed is the mass distribution index of both curves, which is the slope of the Log-Log depiction of the two cumulative curves. The third model, derived from lunar crater data of Morrison and Zinnner (19), is shown as a Log cumulative flux vs. a Log mass distribution. One can observe that for masses < 10^{-12} g the divergence between the three mass models appears to be most drastic. Considerable attention has been given to the variations in the cumulative flux of submicron particles suggested by these models (21). In summary, a bimodal particle distribution may exist near the moon, especially where the in-situ measurements are in selenocentric space.

The next most important step is to use the cumulative flux models to determine the total mass of sporadic interplanetary matter impacting the lunar surface. Hughes (22) has shown that the cumulative flux of particles on a surface (per unit area per unit time) have a mass m is:

$$\Psi = \varepsilon(m)m = Am^{1-\alpha} \ dm. \qquad (1)$$

(where A is a constant and α is the mass distribution index). The Log differential mass flux vs. Log mass curves derived from the three mass models depicted in Fig. 1 are shown in Fig. 2 (20); the total mass flux of sporadic meteoroids impacting the lunar surface is determined with the results give in Table I. (The mass range for each model is 10^{-18} - 10^{+2} g. The information contained in Table I provides the initial basis for a model of the ejecta mass.

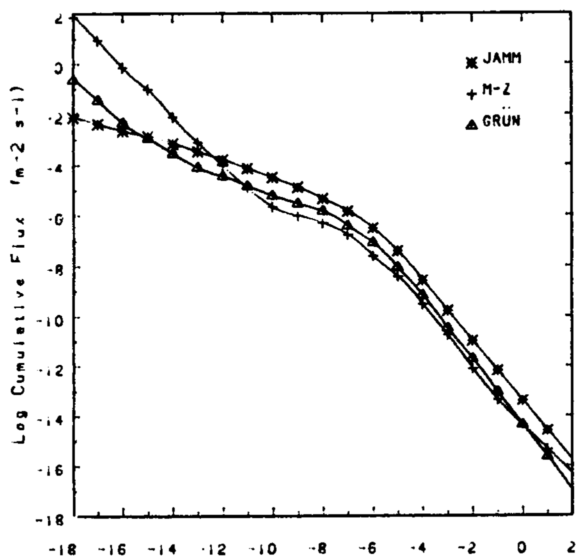

Figure 1. Log Mass (grams)

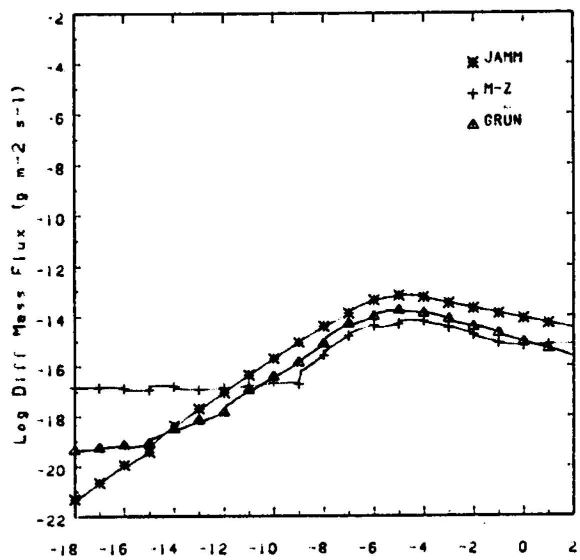

Figure 2. Log Mass (grams)

TABLE I

Model	Mass Flux g/m^2 sec	Total Mass Lunar Surface g / Day
McDonnell	2.5×10^{-12}	8.3×10^{6}
Grun	5.5×10^{-13}	1.8×10^{6}
Morrison-Zinner	2.4×10^{-13}	8.0×10^{5}

Production of ejecta during hypervelocity impact events have always been observed, and there exist a few notable examples (23) of experiments which have measured the physical and dynamic properties of the ejecta. However only a few sources (21) have provided information concerning the dynamics of that portion of the ejecta which has sufficient velocity to escape the moon. The morphology of craters resulting from hypervelocity impact of micron and submicron particles provides a means of determining (21):

1. The total mass flux of ejecta as a function of primary particle mass, and

2. The cumulative mass distribution of the high velocity ejecta.

Velocities of the primary particles were near 4 km/sec. Zook et al. (24) have recently reported results of similar ejecta studies with an impacting velocity of 6.7 km/sec, but with primary incident angle varying between 7 and 90 degrees.

The major difference between the early results and those of Zook is in the amount of total micron size ejecta mass. Zook has found an increase of a factor of two hundred in the number of one-micron ejecta craters per impacting mass at the oblique angles. An additional ejecta parameter that is common to the studies (25,26,24) is an estimate of the cumulative size distribution for the high velocity micron size ejecta from which the important parameter α, the mass distribution index, can be determined. Such an index can be inferred from the information Schneider reported (21). Table II gives the value of α for each reported instance.

TABLE II

MASS DISTRIBUTION INDEX

Richards (25)	0.81
Alexander & Corbin (26)	0.83
Zook et al. (24)	0.81

TABLE III

SOURCE	TOTAL EJECTA MASS FLUX (g/m^2 sec)
Ref. (25) and McDonnell Model	1.24×10^{-15}
Ref. (26) and McDonnell Model	same results as above
Ref. (24) and McDonnell Model	2.5×10^{-13}

Given the total ejecta mass of interest and the mass distribution index, the cumulative flux for the ejecta leaving the moon's sphere of influence can be estimated. This flux can be compared over the ejecta mass range to that of the sporadic micron cumulative flux. Finally, the ejecta spatial density near the lunar surface is given for comparison to that of interplanetary dust flux in Table I. Using the mass flux of Table III and ejecta velocity near the lunar surface of 3 km/sec, Ref. (24) and McDonnell, the spatial densities of the two results in Table III are 4×10^{-19} g/m^3, Ref. (25,26), and 8×10^{-17} g/m^3, Ref. (24). The above results show that the lunar ejecta spatial density (25,26) near the lunar surface is essentially the same as the incoming interplanetary dust spatial density of 3.2×10^{-19} g/m over the same range of mass. In the second case (24), the ejecta spatial density is greater than that of the interplanetary dust over the same range of mass.

TRANSPORT OF LUNAR EJECTA TO THE MAGNETOSPHERE OF THE EARTH

Alexander et al. (14) have presented the results of a study of the dynamics of micron and submicron particles in selenocentric, cislunar and geocentric space which

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shows a significant variation in time of the magnitude of lunar ejecta arriving at the boundary of the magnetosphere. In addition, Corbin (27) determined that the transport time of these particles to the magnetosphere surface varied in such a manneer as to effectively focus the particles due to this temporal variation. For example, 0.3 μm particles that leave the lunar surface when the LPA is about 105° will arrive at the earth's magnetosphere (EMP_s) within 7 days. A 0.05 μm particle released when the LPA is about 155° has a transport time to the EMP_s of less than 2 days (27). Thus, a lunar ejecta flux (LEF_x) of 0.3 and 0.05 μm particles will arrive at the surface of the EMP_s essentially at the same time. Shown in Fig. 3 (14) is a LPA and part of a lunar orbit where a large percent of ejecta moves in orbits that will intercept the magnetosphere.

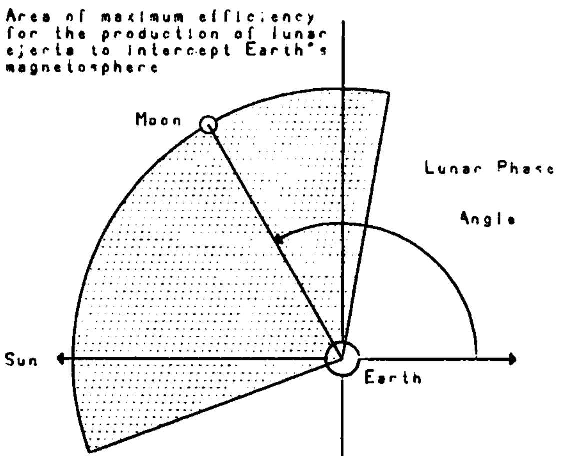

Figure 3.

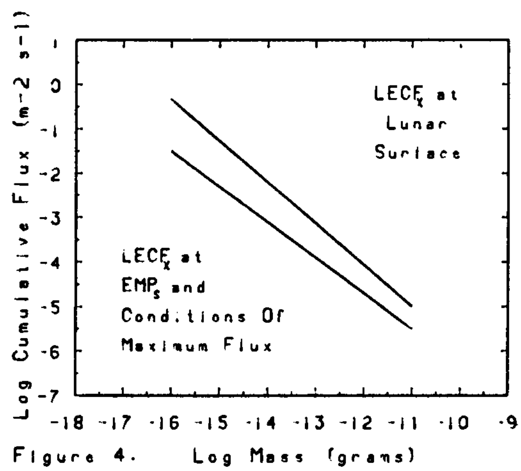

Figure 4.

A sensible qualitative picture combining the percentage ejecta injection from (10) and the transport times from (27) is depicted in Fig. 4 (14). This figure shows a comparison of the lunar ejecta cumulative flux ($LECF_x$) at the surface of the moon and at the surface of the EMP_s. The flattening of the $LECF_x$ from the position near the lunar surface to the EMP_s surface due to the focusing effect is apparent. This flattening of the $LECF_x$ is the result of the orbit selection as a function of lunar ejecta radius and the non-gravitional forces.

When lunar ejecta arrive at the EMP_s surface, they represent the mass leaving the moon at an LPA of 40° to 170° or about 1/3 otfthe time of a lunar orbit. However, the efficient LPA position for lunar ejecta transport with maximum EMP_s interception is between 80° and 160° or over six days of a lunar orbit time, which is approximately 1/4 of a lunar period. When the lunar ejecta mass is intercepted at the EMP_s boundary, the

$LECF_x$ of micron and submicron particles traverses the EMP_S in a time of slightly more than one day. This represents a focusing effect of at least a factor of three, but not greater than a factor of six. The effect discussed above is depicted in Fig. 5a and 5b (14).

In Fig. 5a (14), the percent of lunar ejecta intercepted by the EMP_S of four different size ejecta particles is shown as a function of LPA or position of the moon when the lunar ejecta was created. Fig. 5b (14) shows the percent of lunar ejecta that is intercepted at the EMP_S surface at essentially the same time. The moon is passing through an LPA of 194° ± 6° during this period.

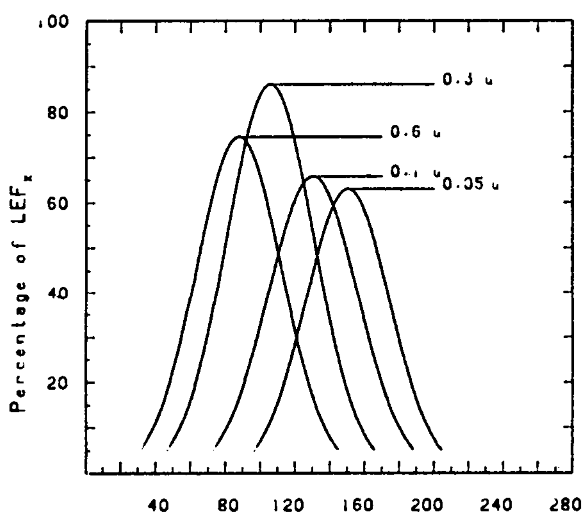

Figure 5a. Lunar Phase Angle

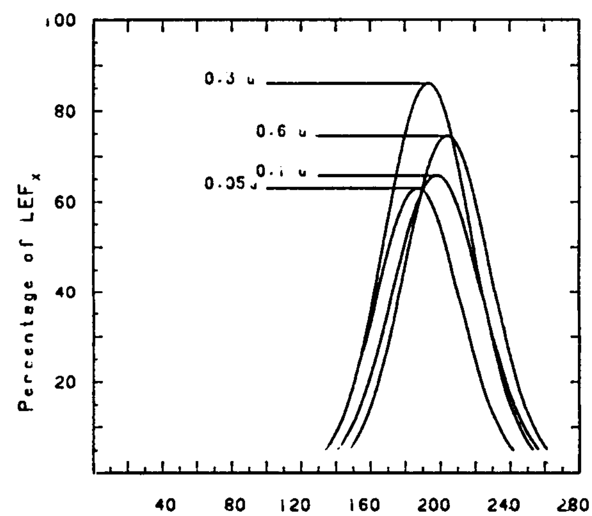

Figure 5b. Lunar Phase Angle

An additional factor of major importance to this work is that of lunar longitude at the time of impact of a primary particle. While the LPA is the major determining lunar position factor, the combination of LPA and longitude produces the maximum $LECF_x$ onto the EMP_S surface. This is demonstrated in Table I where all percentages are calculated for the LPA range (in 10° steps) from 10° to 160° (28).

TABLE I

Lunar Longitude Quarter	Average Percent EMP_s Intercept	Maximum Percent EMP_s Intercept	LPA°
1st	20.230	63.89	100
2nd	27.26	77.78	90
3rd	38.28	94.44	110
4th	33.25	90.28	110

The most important factor regarding sensitivity to longitude is the occurrance of non-random impact flux events. This is quite noticeable for the periods known as major shower periods (29). Initially, the LPA will determine if these ejecta will be transported to the EMP_s surface. For an optimal LPA, the maximum $LECF_x$ will occur when the lunar quarter (by longitude definition) is in the most favorable impact position with respect to the meteor shower radiant. From Table I, a shower radiant that was essentially normal to the 3rd and 4th quarter with an LPA near 110°, would result in greater then 90 percent of the produced ejecta intercepting the EMP_s surface.

CONCLUSIONS

There is ample evidence now to support the concept that the impact of interplanetary dust on the moon's surface creates a significant flux of lunar ejecta which, for nanogram and smaller particles, have lunar escape velocity. When these ejecta are formed during favorable LPAs, i.e. 80° to 160°, a large percent of the total mass penetrates the earth's magnetopause as a "pulse" of lunar ejecta. The pulse occurs for each orbit of the moon. The ejecta source is the total mass of interplanetary dust representing the sporadic meteoroids constantly impacting the surface of the moon. When the earth-moon system is intercepting a major meteor stream, the lunar ejecta flux is significantly enhanced if the "meteor shower" time period coincides with an appropriate LPA period (30). An additional enhancement can occur when the lunar "longitude" is also favorable. The possible concentration of these particles in the inner magnetosphere, measurements to study this enhanced spatial density and possible implications to geophysics phenomena is discussed in the following paper by Alexander et al. (31).

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N89-15008

IMPACT CRATERING IN REDUCED-GRAVITY ENVIRONMENTS: EARLY EXPERIMENTS ON THE NASA KC-135 AIRCRAFT

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As outlined at last year's workshop[1,2], a variety of reasons exist for performing impact experimentation at reduced gravity-levels. The execution of such experiments, however, will require familiarity with reduced-*g* environments, as well as with the idiosyncracies associated with the change in gravitational acceleration. Since there has been little low-*g* cratering experimentation in general[3] and no impact experimentation specifically performed in flight (although some ground-based work has been done[4]), a series of impact-cratering experiments has been initiated on the NASA KC-135 Reduced-Gravity Aircraft. The intent of this program is threefold: (1) to acquire experience in low-*g* experimentation, (2) to develop an observational understanding of the changes in the cratering process at reduced *g*-levels, and (3) to collect scientifically useful data in the process. This report describes the apparatus, the experimental environment on the KC-135, and some early results regarding cratering in sand targets.

The Low-Velocity Impact Facility: The ideal impact facility would utilize a projectile accelerator capable of launching projectiles of a variety of types and sizes over a wide range of impact velocities. The availability of funding for this initial facility, however, required a more modest approach. The accelerator is a Sheridan 5mm pellet pistol, which has been modified to be mounted vertically and fired electronically. Impact velocities of ~50-130 m/s (with 0.96g, cylindrical lead pellets) are attainable by varying the pressurization in the gun's pump chamber. The impact chamber is a 51.8x51.8x45.8-cm aluminum-framework box, with tempered-glass walls to permit photography and viewing of experiments; its lid is hinged for access to the interior. Since this facility does not yet support vacuum capability, all experiments to date have occured at aircraft-cabin pressure, typically 0.83 atmospheres. Data collection relies principally on photography (high-speed motion picture, still, and video cameras), while acceleration and atmospheric-pressure information is recorded digitally with a microcomputer. Projectile velocities are measured *via* interruption of infrared photodiodes separated by a fixed distance; an independent oscillator circuit is used for timing. Experimentation during flight is invariably performed under somewhat hectic conditions due to the compressed timeline necessitated by the aircraft's high rate of fuel consumption; in order to maintain efficiency at a level as high as possible, the computer is also employed as an event sequencer -- operating the cameras, firing the gun, measuring and recording projectile velocities, and recording event times.

Experimental Environment on the KC-135: Gravity levels ranging from -0.1 to ~2 *g*'s can be supported by the KC-135 for tens of seconds; the flight profile is selected by the investigators in concert with the flight crew. Depending on a number of factors related to the overall experimental program on a given flight, up to 50 parabolas can be accommodated on a typical 2.5-hour flight. Moderate- to high-frequency vibrations of noticeable amplitude are minimal during a typical parabolic maneuver, although low-frequency oscillations of varying amplitude around the targeted *g*-level are not unusual (Fig.1). While the pressurized cabin provides a comfortable, shirt-sleeve working environment, normally routine operations are often made more difficult due to the variable-*g* environment. Experimenters have been known to sleep well following a typical flight.

Early Results: The early developmental flights have provided the opportunity to collect limited data on crater dimensions and growth times as functions of *g*-level and impact velocity. A coarse-grained, polymineralic sand (1.57 g/cm^3 and 32.5° angle of internal friction) was employed as the target. Comprised predominantly of quartz and feldspar (see Table 1 for its grain-size distribution), the sand filled the chamber to a depth of 15

* C-2

cm; comparison with earlier findings[4] leads to the conclusion that the volume of target material was sufficient to obviate noticeable edge-effects during formation of the largest craters at 1*g*. No anomalous phenomena that might have been related to the finite target-depth were observed during flight, but this parameter remains to be examined in more detail before serious experimentation is conducted at the lower *g*-levels, especially when higher projectile energies are employed. A total of 27 shots have been performed to date, covering a range of 0.082 to 0.534 *g*'s. Crater dimensions were obtained from 35mm photography after completion of each experiment; crater growth-times were derived through analysis of ejecta-plume shapes from 16mm motion-picture photography at 250 frames/s, yielding a time resolution of 0.04 s. Due to limitations in attainable impact velocities, a variation of only a factor of 6 in impact energy was possible. For comparison, experiments with the JSC Vertical Impact Facility can be performed with impact energies covering almost 4 orders of magnitude. *Crater Diameters:* The limited range of projectile velocities resulted in craters with rim-crest diameters varying over an interval of only 11 to 18 cm. This limited size range nevertheless is sufficient to demonstrate well-defined gravity and velocity (or energy) dependences (Fig. 2). The diameters of craters formed at two fixed energy levels (and velocities, since the projectile mass was constant for each shot) are presented for a range of *g*-levels. Not only does this figure illustrate the inverse relationship between crater diameter and gravitational acceleration, but the relatively unscattered data attest to the suitability of the KC-135 as a scientific test bed: the precision of these data is comparable to those obtained in ground-based laboratories. The slopes of the two least-squares fits -- which are statistically indistinguishable owing to the small number of data points -- are very near the value of -0.165 obtained in ground-based experiments.[4] *Crater Growth-Times:* The times required for crater growth were obtained by counting the number of 16-mm frames from the time of impact to the time that the profile of the ejecta plume near the target surface changed from a continuous, concave-outward curve to a discontinuous intersection between the expanding curtain and the target surface. Data for the same 14 craters are illustrated in Figure 3 and, once again, the small number of actual data points will not permit the assertion that the two slopes are distinguishable. Confidence intervals notwithstanding, both fits are substantially different from that obtained in the drop-platform experiments,[4] which is included in the figure as the dashed line. The slopes of the fits to the KC-135 data are also outside the theoretical limits as determined through dimensional analysis;[5] the causes of these differences are not yet understood. The target sands, for example, were different in both sets of experiments represented in Fig. 3; it has been demonstrated that variations in bulk density and angle of internal friction can play a nontrivial role in determining the outcome of a cratering event.[6] The drop-platform data[4] were collected with impact velocities of 6.4 km/s, while those displayed here were at a maximum of 0.111 km/s. Finally, there is a small but undetermined effect due to the atmospheric pressure differences between the two experiment series. On the other hand, the limits placed on the gravity exponent by the dimensional analysis are $-4/7$ to $-5/8$, which is expected to hold "for all materials and impact conditions."[5] Clearly, more work will be required to determine whether these variations are indeed real and, if so, to evaluate their possible causes.

Summary: Impact experimentation on the NASA KC-135 Reduced-Gravity Aircraft has been shown to be possible, practical, and of considerable potential use in examining the role of gravity on various impact phenomena. With a minimal facility, crater dimensions and growth-times have been measured, and have demonstrated both agreement and disagreement with predictions. A larger facility with vacuum capability and a high-velocity gun would permit a much wider range of experimentation.

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Table 1. Grain-size Distribution of target sand

Size (mm)	Mass Fraction
>0.500-1.000	0.264
>0.250-0.500	0.660
>0.125-0.250	0.075
≤0.125	0.001

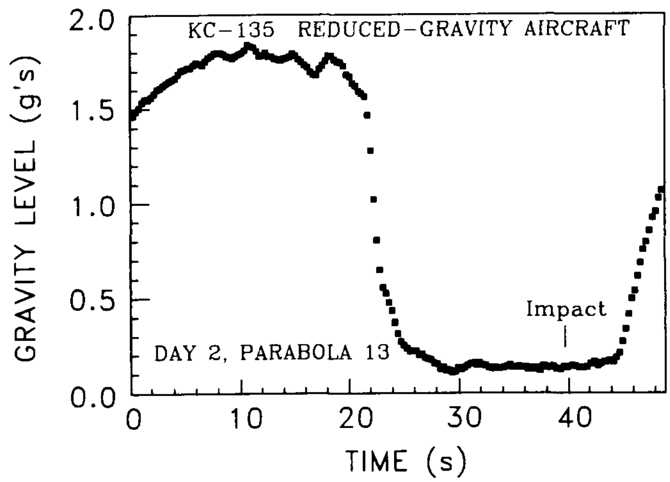


Figure 1. An example of the acceleration history during an impact experiment on the KC-135. The g-level on the vertical axis was sampled 4 times per second; the time of gun firing and impact is indicated just before 40 s. Note the small oscillations around the targeted level of 0.16g.

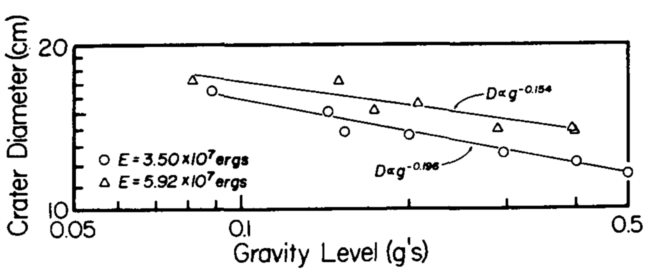
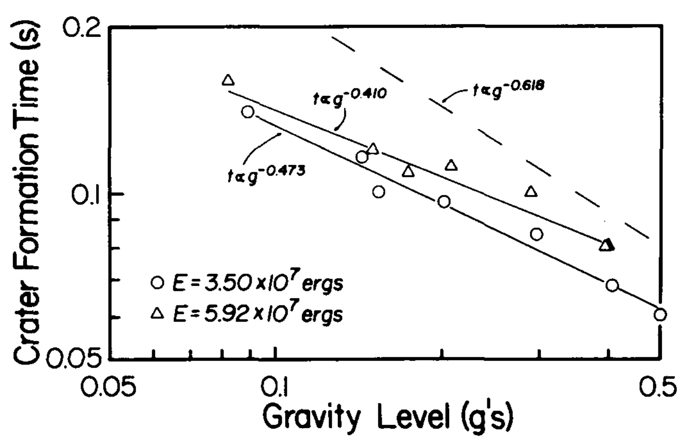


Figure 2. Crater diameter as a function of g-level for two fixed impact energies. The lower energy impacts occurred at ~83 m/s, while the others took place at ~111 m/s. These slopes can be compared with -0.165, the value obtained from drop-platform experiments.[1] Note the modest scatter in the data, attesting to the stability of the KC-135 as a test bed.

Figure 3. Crater formation-time as a function of g-level for the same craters treated in Figure 2. The dashed line possesses the slope determined for high-velocity impacts in the drop-platform experiments.[1] The slopes for the KC-135 data are beyond the limits suggested by dimensional analysis,[5] but the reason for the disparity is unclear. See the text for possible causes.



N89-15009

LOW-GRAVITY IMPACT EXPERIMENTS: PROGRESS TOWARD A FACILITY DEFINITION

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Innumerable efforts have been made to understand the cratering process and its ramifications in terms of planetary observations, during which the role of gravity has often come into question. Well-known facilities and experiments both have been devoted in many cases to unraveling the contribution of gravitational acceleration to cratering mechanisms. Included among these are the explosion experiments in low-gravity aircraft performed by Johnson et al.(1), the drop-platform experiments of Gault and Wedekind(2), and the high-g centrifuge experiments of Holsapple and Schmidt.(3,4) Considerable insight into the effects of gravity, among other factors, has been gained through studies exemplified by those cited above. Even so, other avenues of investigation have been out of reach to workers confined to the terrestrial laboratory. It is in this light that the Space Station is being examined as a vehicle with the potential to support unique and otherwise impractical impact experiments. This report summarizes the results of studies performed by members of the planetary cratering community; their names and affiliations are listed below.

Scientific Rationale and Experiment Types -- The microgravity environment is useful in two basic ways. First, with some coaxing, it can permit direct experimentation at the gravity levels characteristic of the vast majority of planetary objects in the Solar System. Second, virtual weightlessness is a factor that enables the execution of experiments that are inordinately difficult or practically impossible to accomplish in a constant 1-g environment. Thus, there are three basic types of impact experiments that could be performed in a Space Station-supported laboratory: direct simulation (of asteroidal regoliths, for instance), process studies (e.g., collisional disruption of weakly bound, free-floating objects), and examination of scaling relationships (the control of crater size and geometry, for example, by forces that are safely negligible in higher gravity fields, such as electrostatic attraction). It must be kept in mind that the overwhelming majority of experimental data have been collected at 1-g. Empirical estimates of ejecta-deposit thicknesses, for instance, rely primarily on terrestrial impact- and explosion-cratering data.(5,6,7) On the other hand, theoretical predictions exist (8,9), but they remain to be tested at different gravity levels.

The Space Station Impact Facility -- The design of an impact facility for the Space Station is being pursued within the framework of the desired capabilities and goals of experimentation that would be performed with it. Among the requirements imposed by the group are

- High impact velocities (at least 6 km/s)
- As large an impact chamber as possible (to accommodate, for instance, the large craters that would be formed at low gravity levels)
- A variety of data-gathering methods (film, video, oscillograph, digital)
- Maximum flexibility in accommodating targets of different types (ranging from massive containers of noncohesive material to solid, free-floating objects)
- Peak electrical power capability of ~25 kW (necessary for short periods of time for chamber lighting and high-speed camera operation)
- Ability to support acceleration levels over the range of 0-0.2g.

Discussion -- These were levied with minimal restriction of the definition process to detailed Space Station capabilities as currently envisioned. Thus, it is a virtual certainty that actual vehicle performance will result in some rethinking of these and other requirements. In this vein, the Initial Operational Capability (IOC) version of the Space Station will be considerably more spartan in its ability to support the sort of facility described above. Nevertheless, a variety of very interesting experiments could still be performed; in particular, those not requiring variable gravity levels would be well-suited to the IOC facility. Not only would they provide new scientific data, but they would also serve to establish experimental procedures in the Space-Station environment. This experience would then provide a valuable foundation for operations with the expanded facility on the post-IOC Station.

At this early stage in the definition of the facility, the type of projectile accelerator is uncertain; rapid advances in railgun and other related technologies portend a precarious future for light-gas guns, especially in terms of the potential for high velocities exhibited by the former. (Should the electromagnetic accelerators be incorporated, their penchant toward high-velocities might permit their use in meteor studies, in which projectiles of various physical properties would be launched into the atmosphere. The resulting artificial meteors would then be examined simultaneously from below and above.)

The requirements of a large target chamber and variable gravity are somewhat uncompromising in an engineering sense. It is likely that centrifugal force would be employed to yield the desired accelerations in the post-IOC version, but the large volume required essentially eliminates simple centrifuges as candidate mechanisms. It is suggested instead that a detachable module or modular array be included as part of the post-IOC the Space Station, carrying its own guidance and propulsion capability. It would then separate from the Station to a safe distance and "spin up" to generate the desired g-level. Numerous experiments needing variable accelerations would benefit from this capability.

A number of technical areas have been identified which could provoke some difficulties unless studies are undertaken to determine remedial solutions or procedures. Target preparation and handling, for instance, especially in the case of fragmental or liquid materials, will pose some challenges; not only would it be a more difficult matter to fabricate a target of sand or some other fragmental material in low to zero gravity, but the floating silicates would pose a nontrivial health hazard. The absolute size of the target chamber is still somewhat in question, since theoretical predictions and extrapolations of experimental data are the only sources of information on crater size at the low g-levels that would be employed. The issue is complicated somewhat by the likelihood that stress waves reflected from the walls of the target containers could be relatively more severe than their generally ignorable counterparts in the terrestrial laboratory.

Many of these technical challenges could be approached through judicious experimentation on the NASA KC-135 Reduced Gravity Aircraft and/or the large NASA drop towers. These facilities can provide support over a wide range of experiment conditions and gravity levels, permitting engineering, procedural, and, most significantly, scientific questions to be addressed in some detail. With the benefit of such experiences, planning for the Space Station facility could be carried out with substantially more confidence.

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N89 - 15010

COSMIC DUST COLLECTION WITH A SUB SATELLITE TETHERED TO A SPACE STATION

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The number concentration and density of 1 micron and submicron sized grains in interplanetary space, as well as their relation to the larger zodiacal dust particles, and the importance of the Beta meteoroid phenomenon are currently being questioned (1,2).

Current stratispheric collection with balloons and a high altitude aircraft has resulted in the accumulation of several hundred (perhaps a thousand) extraterrestrial particles larger than 10 microns; however, there are inherent problems with using this collection technique for the smallest particles less than 1 or 2 microns in size:

1) Strong contamination from small terrestrial particles in the stratisphere

2) Loss of time resolution and mixing of particles from different sources resulting from the long settling times of the particles as they fall slowly into the stratosphere from the upper atmosphere where they are decelerated

Attempts to obtain samples of the smallest micron and sub micron sized cosmic dust particles in space with collectors on board the space shuttle or satellites such as the Long Duration Exposure Facility (LDEF) are subject to two major difficulties:

1) Contamination by shuttle debris, rocket exhaust, and other orbiting man made debris

2) Hypervelocity impact speed on the order of tens of km/sec. resulting in destruction of the smallest particles with only small amounts of chemically fractionated impact debris remaining around impact craters.

A superior approach to the problem of how to collect large numbers of intact micron and sub micron sized cosmic dust particles in real time while avoiding terrestrial and man made contamination would be to employ a tethered subsatellite from a space station down into the earth's upper atmosphere. In this way orbital contaminants from the space station could be taken of the gradual deceleration of the hypervelocity particles by the earth's upper atmosphere.

Such a sub satellite tied to the space shuttle by a 100 km long tether is being developed by the Marshall Space Flight Center for the acquisition of upper atmospheric data. The author has previously proposed that cosmic dust collectors be affixed to the outside of such a sub satellite tethered to the space shuttle (3,4,5). However the maximum duration of deployment into the upper atmosphere is likely to be on the order of only a few hours, which is much shorter than what would be possible (several days) if the sub satellite were tethered to a space station maintaining altitude indefinitely. The number of particles collected intact or nearly so in this fashion should be at least a factor 10 greater than from the space shuttle. It is also possible that a permanent space station would allow the use of a tether even longer than the 100 km. long one scheduled for use on the space shuttle. This would allow even deeper penetration into the earth's upper atmosphere allowing for even more deceleration to be imposed on the hypervelocity partricles before impact onto the collectors. Of course the relative impact velocity is not likely to be less than the orbital velocity of the sub satellite except for those particles within two cones of solid angle alpha, one in the forward direction and one to the rear, whose cosmic velocity vectors are essentially parallel to and within a few km/sec of the satellite's. Laboratory impact simulation experiments have shown that high density particles impacting with velocities on the order of a few km/sec can survive impact intact or nearly so in appropriate target materials.

It should be noted that the same tethered collectors could also be employed to study the composition and flux of man made earth orbiting debris in any direction within 100 km or so of the space station. This would make it possible to monitor the build up of any debris belt in low earth orbit.

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ELECTRICAL CONDUCTIVITY OF CARBONACEOUS CHONDRITES AND ELECTRIC HEATING OF METEORITE PARENT BODIES*

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Electromagnetic heating of rock-forming materials most probably was an important process in the early history of the solar system. Electrical conductivity experiments of representative materials such as carbonaceous chondrites are necessary to obtain data for use in electromagnetic heating models.

The electrical conductivity of samples of the Murchison and Allende carbonaceous chondrites is 4 to 6 orders of magnitude greater than that of rock forming minerals (e.g., olivine) up to 700°C. The remarkably high electrical conductivity of these meteorites is attributed to carbon at grain boundaries. Much of this carbon is produced by pyrolyzing hydrocarbons at temperatures in excess of 200°C. As the temperature increases, light hydrocarbons are driven off and a carbon-rich residue, or char, migrates to the grain boundaries thus enhancing the electrical conductivity.

With the assumption that carbon was present at grain boundaries in the material that comprised the meteorite parent bodies, we have calculated the electrical heating of such bodies as a function of body size and solar distance using the T-Tauri model of Sonett and Herbert (1977). Input conductivity data for

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the meteorite parent body were the present carbonaceous chondrite values up to about 800°C and the electrical conductivity of olivine above 800°C. The results indicate that bodies up to 500 km in diameter would be heated to 1100°C (melting point of basalt) out to about 3 AU in times of one million years or less. The distribution of asteroid types as a result of these calculations is consistent with the distribution of asteroid compositional types inferred from remote sensing (Gradie and Tedesco, 1982); carbonaceous chondrite asteroids peak at about 3 AU, more siliceous asteroids peak at about 2.4 AU.

One concern with these calculations is the use of olivine conductivity data at temperatures in excess of 800°C. We were required to use olivine conductivity at these temperatures because the conductivity of all carbonaceous chondrite samples decreased precipitously toward the olivine values. Two factors could be responsible for this decrease. These are oxidation of carbon in the CO_2/CO gas mixture or volatility of carbon. We are unable to separate these effects in gas mixing systems, vacuums, or inert gases because of the extremely low oxygen fugacity--less or equal to about 10^{-15} Pa--required to prevent the oxidation of carbon at 800°C. In addition, the precipitation of carbon from the more reducing CO/CO_2 gas mixes required to produce this low oxygen fugacity interferes with the conductivity measurement.

The environment in the wake of the Space Station can be exploited to produce oxygen fugacities less than 10^{-15} Pa (Oran et al., 1977). An experimental package consisting of a one square meter shield attached to a 15 cm diameter by 40 cm long furnace and tied to a conductance bridge, furnace controller, and digital voltmeter inside the Space Station via umbilical cable could make the required measurements. Because heating rates as low as 0.1°C/hour are required to study kinetics of the pyrolysis reactions which are the cause of the high conductivity of the carbonaceous chondrites, experimental times up to 3 months will be needed.

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ELECTRICAL CONDUCTIVITY OF CHONDRITIC METEORITES*

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The electrical conductivity of samples of the Murchison and Allende carbonaceous chondrites is 4 to 6 orders of magnitude greater than rock forming minerals such as olivine for temperatures up to 700° C. The remarkably high electrical conductivity of these meteorites is attributed to carbon at grain boundaries. Much of this carbon is produced by pyrolyzation of hydrocarbons at temperatures in excess of 150° C. As temperature increases, light hydrocarbons are driven off and a carbon-rich residue or char migrates to the grain boundaries enhancing electrical conductivity.

Assuming that carbon was present at grain boundaries in material which comprised the meteorite parent bodies, we have calculated the electrical heating of such bodies as a function of body size and solar distance during a hypothetical T-Tauri phase of the sun. Input conductivity data for the meteorite parent body were the present carbonaceous chondrite values for temperatures up to 840° C and the electrical conductivity values for olivine above 840° C.

Results of these calculations indicate that bodies up to 500 km in diameter would be heated to 1100° C (melting point of basalt) out to about 4 AU in times of one million years or less, which is the hypothesized duration of the T-Tauri phase of the sun. The distribution of asteroid types as a result of these calculations is consistent with the distribution of asteroid compositional types inferred from remote sensing: carbonaceous chondrite asteroids peak at about 3 AU, more siliceous asteroids peak at about 2.3 AU.

One concern with these calculations is the use of olivine conductivity data at temperatures in excess of 840° C. We were required to use olivine conductivity at these temperatures because the conductivity of all carbonaceous chondrite samples decreased perciptiously toward the olivine values. Two factors could be responsible for this decrease: oxidation of carbon in the CO_2/CO gas mixture or volatility of carbon. We are unable to separate these effects in gas mixing systems, vacuums, or inert gases because of the extremely low oxygen fugacity- less or equal to about 10^{-15} Pa- required to prevent the oxidation of carbon at 840°C. In addition, the precipation of carbon from the more reducing CO/CO_2 gas mixes required to produce this low oxygen fugacity interferes with the conductivity measurement.

The environment in the wake of the shuttle or space station can be exploited to produce oxygen fugacities less than 10^{-15} Pa using a molecular shield. Such an environment would be ideally suited to perform electrical conductivity measurements at high temperature in an atmosphere which would not interfere with that measurement.

*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

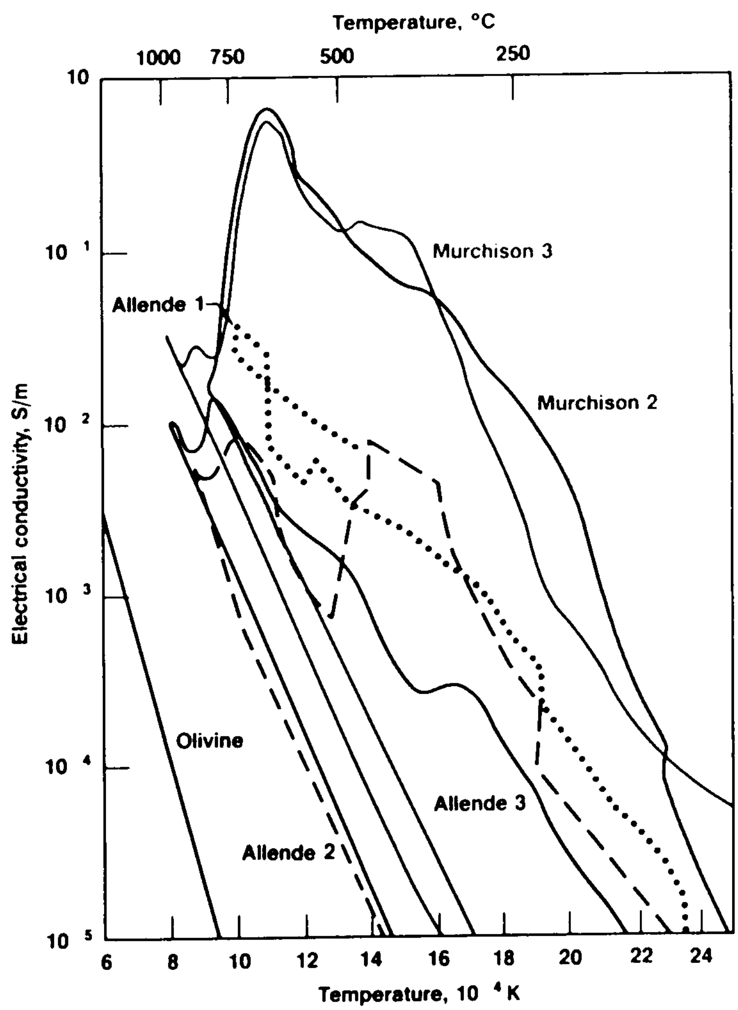

Fig. 1

Comparison of electrical conductivity as a function of temperature for samples of two carbonaceous meteorites (Murchison and Allende) and for terrestrial olivine. Note that all carbonaceous chondrites show very high electrical conductivity, compared to olivine, at temperatures below about 800°C. Above this temperature, loss of carbon causes conductivity to decrease with time toward values observed for single-crystal olivine.

N89-15013

THE ORBIT PROPERTIES OF COLLIDING CO-ORBITING BODIES

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It is generally assumed that an ensemble of small bodies located in similar Keplarian orbits will, because of collisions, tend to disperse into more and more dissimilar orbits. For example, it is thought that the asteroids may represent the remnents of a few larger bodies that broke up or failed to fully accrete. Alfvén and Arrhenius (1976), Alfvén (1971), and Baxter and Thompson (1971,1973) and others have challanged this. Alfvén (1971), maintains that for the case where the time between collisions is longer than the orbit period and the collisions are essentially inelastic the orbits and velocities will become more simiiiar. This gives rise to the concepts of negative diffusion and jet streams. Figure 1 taken from Alfvén and Arrhenius (1976) illustrates the problem: Does the arrow of time lead from figure a. to b. or vice versa.

We propose that this question might be investigated experimentally using the space station. An ensemble of small bodies or particles might be released gently from a central location in a large chamber, much like the breaking of billiard balls (see Figure 2). The particles would then co-orbit and occasionally collide. Their subsequent behavior could be monitored by several video recorders, their linear and angular velocities before and after collisions calculated and their general behavior studied. The experiment might be varied by using particles of varying elasticities (coefficient of restitution), varying masses, and different initial relative velocities. The particles would be colored to make it easy to follow their motion and could be spherical or irregular shaped and smooth or rough. Their size might be approximately that of billiard balls. Materials could be found which would break up on collision and the fate of the collision products followed and the size distribution studied. U.V. lights and gas could be introduced to simulation charging and drag conditions found in space or near a primordial planet.

Figure 3 illustrates the possible relative motion of two bodies released in this fashion. The expected ultimate configuration for this simple case is that the bodies line up again at rest in the center of the chamber.

The proposed experiment requires a large spherical or cylindrical chamber about 14 feet (4.66 m) in diameter with three cameras looking into the chamber along three orthogonal axes. The particles will be in free orbits about the center of the chamber, therefore, the vertical or horizontal motion of the chamber, due to loss of altitude from drag or thrusting must not exceed 3 feet (1 m) in 10 orbits (~15 hours). The experiment may need to run for as long as 50 orbits. It requires only initiation and periodic checks by the crew to insure the cameras are operating. Power is required to operate the cameras and lights, 50 watts with a 10% duty cycle, and to initiate release of the particles, 5 watts for 5 seconds.

This experiment could yield results of fundamental importance for theories of the origin of the planets, the asteroids, comets and probably ring systems.

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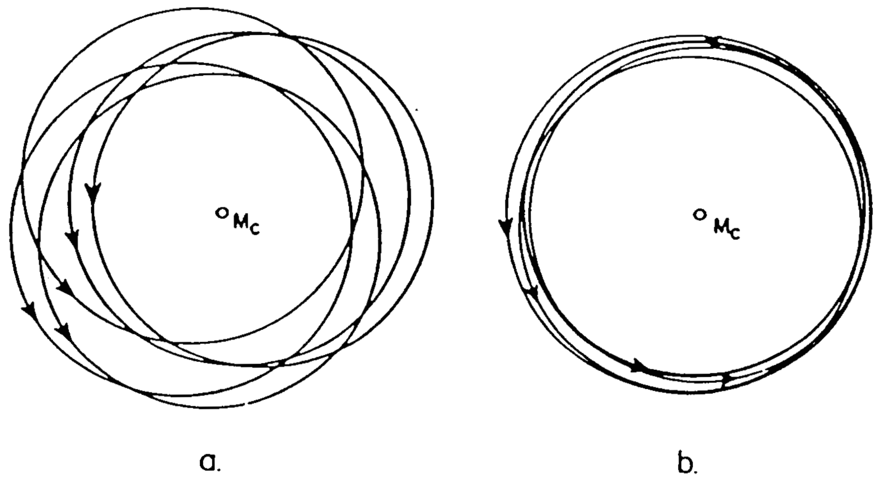


Figure 1

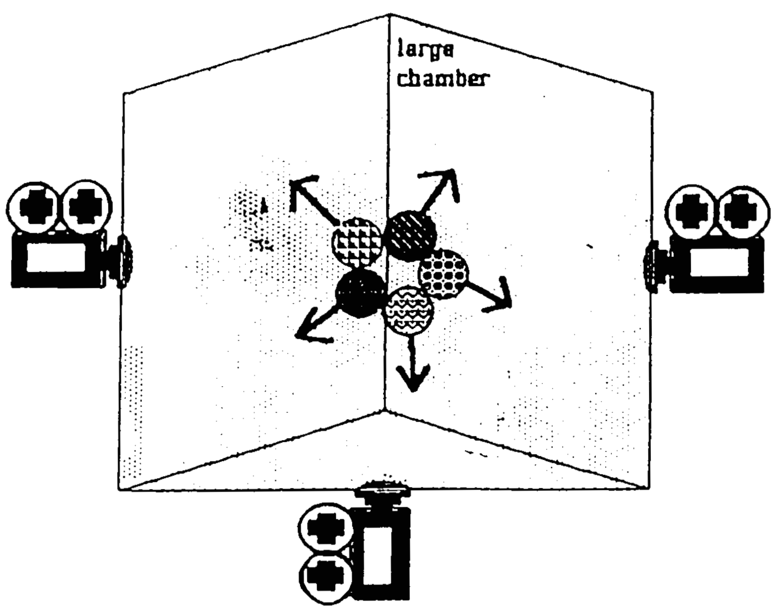
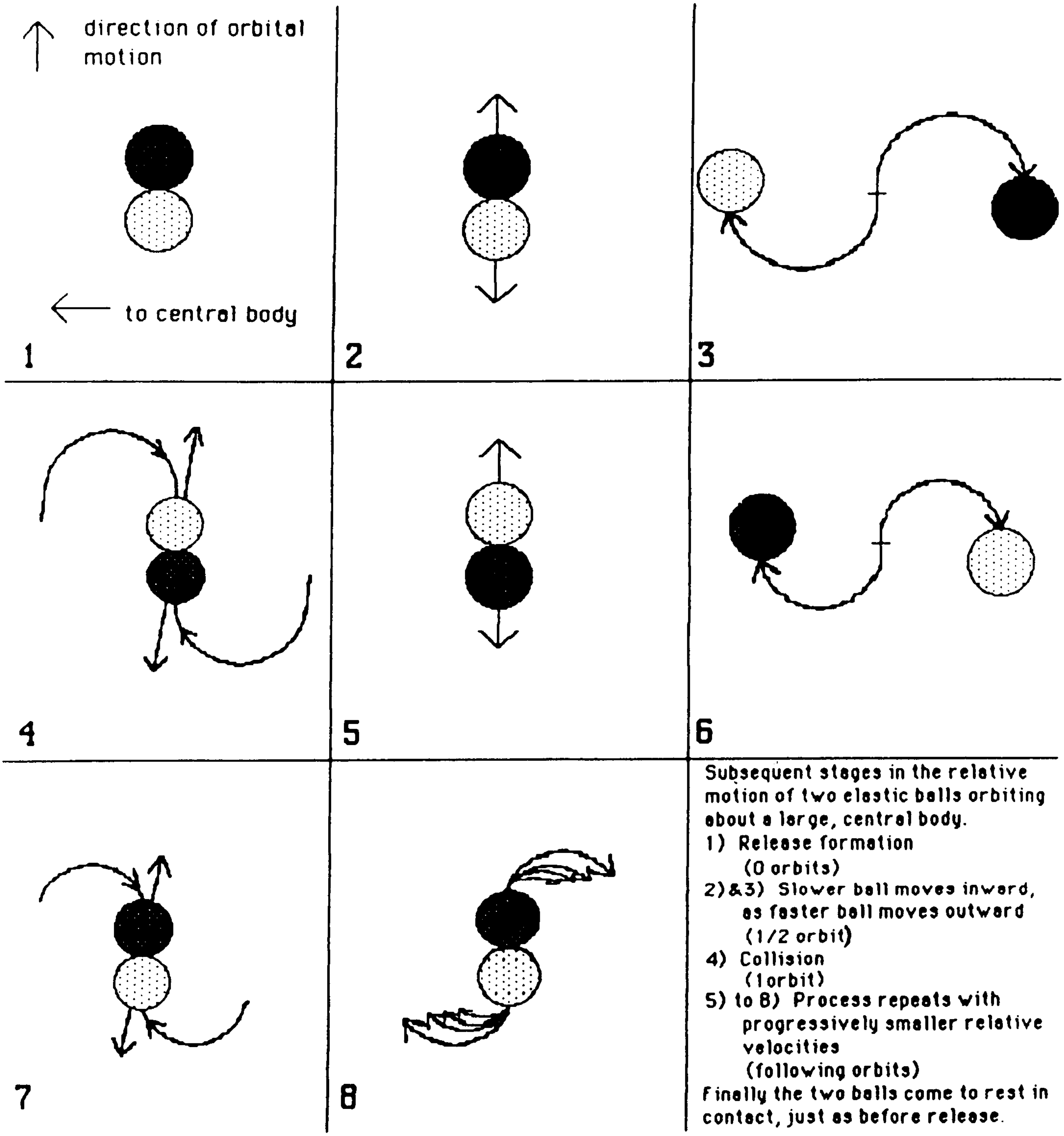


Figure 2



Subsequent stages in the relative motion of two elastic balls orbiting about a large, central body.

1) Release formation
(0 orbits)

2)&3) Slower ball moves inward, as faster ball moves outward
(1/2 orbit)

4) Collision
(1orbit)

5) to 8) Process repeats with progressively smaller relative velocities
(following orbits)

Finally the two balls come to rest in contact, just as before release.

Figure 3

N89-15014

VOLATILIZATION-DEVOLATILIZATION REACTIONS

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Experiments that explore chemical and physical aspects of volatilization reactions that require the microgravity and low pressure in or near the projected Space Station are proposed.

Chemical Aspects:

We envisage a program of experiments utilizing near zero pressure conditions available with molecular shield technology (see Duba, Electrical Conductivity. . .,this report) attached to the Space Station to study:

a) reaction rates of mineral devolatilization. Two mineral groups, the amphiboles and micas (and all the sheet silicates in general) are primary carriers of H_2O and F in rock-forming processes. The important reaction type: hydrous solid = anhydrous solids + vapor, studied over a range of temperatures from 1300°C to as close to space-ambient temperature as reaction rates can be measured will provide fundamental limiting data on the energetics of the crystalline state. The amphiboles and micas can be synthesized in their pure OH- and F-forms so that comparative data of great value could be derived from experimental studies in the Space Station. The time frame for the experiments will be a few days to 60 days. Gravity control is not essential, but pressures less than 10^{-10} Pa are required.

b) the equilibrium vapor pressure of volatile-bearing mineral species. Completing equilibrium studies at very low pressures would allow fixation of the reaction boundaries - expressed, for example, in conventional f_{H2O}-1/T diagrams - in parts of the diagrams not accessible on Earth. These experiments would utilize pressures from station-ambient preferably to < 10^{-10} Pa.

Physical Aspects:

We suggest a program focused on the precipitation, growth, and recrystallization of various cosmically important minerals, particularly ices of H_2O and CO_2, and mixtures of these, to study:

a) textural patterns and their evolution with sequential modification of boundary conditions. Meteorites, and especially asteroidal material subsequently to be obtained, can provide information on their formation histories as well as that of the solar system through detailed textural studies. These studies will have to be calibrated against synthetically produced textures from the Station experiments.

These experiments would need both controlled gravity (~10^{-5}g) and access to pressure ranges from station-ambient (~1 bar) to space ambient (molecular shield to obtain <10^{-10} Pa) over time-scales of 1 day to 60 days. Slowly rotating furnaces would probably prevent crystal settling conditions for such long periods.

b) scattering, absorption, and reflectivity of radar and other wavelength radiation. Ices and particulate silicates are important constituents of dispersed planetary matter. The proposed measurements are to provide baseline data for all our remote sensing studies of these materials, particularly fragile aggregates of such material which could not be synthesized or maintained under 1 g. Initial experimental requirements are the same as under the sections above. Subsequent to synthesis radiation sources and detectors on or near for comparable analysis the station will be required in some cases before returning samples to earth.

Technical Requirement Summaries:

Volume:	2 m^3 for the first three experiments
Mass:	Estimated 10-30 kg for assembly
Temperature:	Space-ambient to 1300^oC
Pressure:	Space-ambient (<10^{-10} Pa) to station ambient
g-level:	10^{-4} to 10^{-5} g for certain experiments. Rotation of the sample may be required to offset effects of density aggregation on longer (month +) experiments.
Duration:	Experiments will last from about 1 day (possibly even hours at T > 1000^oC) to 60 days.
Instrumentation:	Power controllers, continuous temperature and pressure measurements down to the

space-ambient, gas analysis (mass spectrometry), gas pressure controllers and flow rate regulators.

Crew Interaction: Conditions during experiments can be controlled automatically, but sample changing and periodic human monitoring required. Some physical measurements will have to be performed by crew.

N89-15015

SMALL LINEAR WIND TUNNEL SALTATION EXPERIMENTS: SOME EXPERIENCES

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Since the wind tunnels proposed to be used for the Space Station Planetology Experiments are of a rather limited size, some experience and techniques used for saltation experiments in a small linear wind tunnel may be of interest. Three experiences will be presented. The first concerns a length effect of saltation mass flux in which the size of the wind tunnel exaggerates the physical process taking place. A second experience concerns a non-optical technique that does not interfere with flow and by which momentum and mass fluxes to the floor may be measured. The technique may also be used to calculate saltation flux (using appropriate assumptions). The third experience concerns the use of the momentum equation to estimate momentum fluxes by differences.

1. A length effect exaggerated by wind tunnel dimensions.

A feedback mechanism that increases mass flux of saltating particles with distance exists for sufficiently fast moving air passing from a smooth floor to a surface of erodible sand. Absorption of momentum by sand starting to move in saltation increases the apparent aerodynamic roughness height. This increase of roughness height corresponds with increased momentum flux from the air which makes a larger saltation mass flux possible. P. R. Owen theoretically showed this feedback mechanism to be exaggerated by the presence of a wind tunnel ceiling. His theory agrees quite well with experimental results of a small cross section linear wind tunnel.

2. An approximate method for fast response measurement of saltation particle flux.

A fast time response sensor may be used to count the number of impacts on an area of floor as well as to measure the momentum flux from impacts. It has the capability of furnishing data to a method by which the horizontal flux of mass moving in saltation for monodisperse particles can be estimated. The sensor has a large advantage in that it does not interfere with the flow in the wind tunnel. A disadvantage of the estimation method is that it must assume a relationship of saltation trajectories to convert the signal into mass flux information. The method uses the assumption for monodisperse particles that saltation length is proportional to the square of particle speed at impact with the surface. The mean particle speed at impact with the surface is assumed to be proportional to the momentum flux divided by the mass flux. It is assumed that mass flux is proportional to number of impacts times the mass of each particle.

The method gives a time series of mass flux of saltating particles. A typical run shows a rapid increase of particle mass flux corresponding to increase of air speed after turning on the wind tunnel fan, followed by a period of steady mass flux, followed by a decay of mass flux as the particles are depleted from the wind tunnel.

3. An attempt to use a direct momentum flux measuring device to evaluate momentum fluxes by using the momentum equation.

By measuring several terms of the momentum equation, momentum fluxes may be estimated by evaluating all but one of the terms of the momentum equation; the difference of terms is the quantity estimated. For example, the momentum equation was used to estimate the momentum flux to the floor of a rectangular wind tunnel as follows: Floor stress = upwind wind momentum flux - downwind wind momentum flux = ceiling stress + pressure differential integrated over the wind tunnel cross section - downwind particle momentum flux. In the example, downwind particle momentum flux was measured using a direct momentum integration device. The method suffered, however in that the difference, the floor stress, was a small difference of large quantities all having experimental errors. Results show that the method is unreliable for distances smaller than 150 cm in a linear wind tunnel and that the estimate has large error limits. It was concluded that direct measurements were preferable where they can possibly be made.

N89-15016

IMPACT EXPERIMENTATION AND THE MICROGRAVITY ENVIRONMENT: AN OVERVIEW

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Impact is an ubiquitous physical process in the solar system. It occurs on all solid bodies and operates over a spectrum of scales, influencing geologic processes ranging from accretion, the early evolution of planetary bodies, the petrogenetic and spatial relations of lunar samples, the surface characteristics and interpretation of spectral data of asteroidal bodies, to the nature of some meteorites. Understanding impact phenomena is therefore paramount in constraining and underpinning a large number of research efforts into fundamental problems in planetary geology. Gravity is an important parameter in impact processes. For example, in cratering it affects the size of crater excavation, the post-excavation modification of the cavity by gravitational collapse, the spatial distribition of ejected materials, and the effectiveness of this ejecta in producing secondary cratering events. With few exceptions (Gault and Wedekind, 1977) previous experimental studies of cratering processes have been undertaken at gravitational accelerations of 1g or higher. These are not the gravity conditions occurring on most solid bodies in the solar system. The physical environment offered ultimately by Space Station represents an unique opportunity to extend the experimental aspect of impact studies into the microgravity (<1g) regime.

Previous and current experimental studies of impact phenomena address a variety of problems. The bulk of impact experimentation, however, has been concerned with crater growth and scaling. Experimental data have established that at impact energies above $\sim10^{18}$-10^{19} ergs (equivalent to the impact of an iron meteorite in the meter-size range impacting at 20 km s^{-1} in a 1g environment), crater excavation occurs in the so-called "gravity regime", where target strength effects are unimportant (Schmidt, 1980). This condition is simulated experimentally by using low strength materials, such as sand or water, and by the use of elevated gravitational accelerations. The effect of elevated gravity is to displace the onset of the gravity regime to lower energies. Such experimentation has led to the development of scaling relations, where cratering efficiency is related to a dimensionless parameter which includes the effects of projectile velocity and size, and gravitational acceleration.

It has been sugggested recently that additional parameters such as the shape of the experimental projectile (Schultz and Gault, 1985) and variable energy losses due to waste heat in the target (Cintala and Grieve, 1984) are not fully accounted for in the current dimensionless parameters. Thus it is important to continue work in this area. The opportunity to conduct new experiments at gravities directly applicable to that of planetary bodies will contribute to determining and refining the relevant scaling relations for large craters. Apart from their importance in problems concerned with cratering mechanics, such relations are required to correctly relate crater densities on different solar system bodies to absolute surface ages (Basaltic Volcanism Study Project, 1981).

A further advantage of the microgravity environment is that, for a given impact event, reduced gravity increases the crater growth time. It will be possible, therefore, through high-speed photography to observe the crater growth and ejecta dynamics in considerably more detail than in previous 1g experiments. This will lead to a better understanding of the relative importance of rebound and collapse phenomena in crater formation and the nature of the ejecta plume as an erosional and depositional agent.

In the low strength materials used in impact experiments under terrestrial conditions, gravitational forces dominate other bonding forces, such as surface tension, electrostatic effects etc. This may not be the case under highly reduced gravity conditions, which prevail on small asteroidal bodies. Even if current dimensionless scaling relations are shown to be substantially correct for large planetary craters, they can not be applied to the energy regime associated with small cratering events. Cratering experiments at highly reduced gravities, corresponding to asteroidal bodies, will therefore provide basic and currently unavailable information on cratering and regolith development or lack of it on these bodies.

Previous experimentation provides little or no information on the spatial distribution, source region and physical state of ejecta under differenct gravity conditions. The few experiments designed to address these fundamental questions all have been undertaken at 1g (Stoffler et al., 1975). Similarly, the only direct observational data on these questions are from terrestrial craters. It is well-established that for a specific impactor size and velocity and target materials, crater size will increase with decreasing gravity. However, peak shock pressures and the spatial distribution of shock isobars in the target are not a function of gravity and will remain constant. They are a function of impact velocity, pulse length and target characteristics. The reduced gravity environment afforded in near-earth orbit provides an opportunity to consider the questions of ejecta source and shock state and its final distribution under varying gravitational accelerations. These questions are highly germane to problems such as the physical and thermal state of ejecta blankets and regolith development on both planetary and smaller bodies. These relate directly to questions in lunar sample and meteorite analyses and the interpretation of remotely-sensed spectral and geochemical data.

The microgravity environment also provides a new and potentially rewarding area of impact experimentation not previously possible. Through the use of free-floating targets, it may be possible to explore in detail phenomena associated with the collision of bodies. Such experiments can address questions regarding early and late accretional processes, catastrophic disruption and asteroidal evolution, as well as the effects of large impacts on the momentum and spin of the target bodies. The last question is of considerable topical interest with respect to the hypothesized origin of the moon by a Mars-sized impact on the early Earth.

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N89-15017

EXOBIOLOGY EXPERIMENT CONCEPTS FOR SPACE STATION

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The exobiology discipline uses ground-based and space flight resources to conduct a multidiscipline research effort dedicated towards understanding fundamental questions about the origin, evolution, and distribution of life and life-related molecules throughout the universe. Achievement of this understanding requires a methodical research strategy which traces the history of the biogenic elements from their origins in stellar formation processes through the chemical evolution of molecules essential for life to the origin and evolution of primitive and, ultimately, complex living species. Implementation of this strategy requires the collection and integration of data from solar system exploration spacecraft and ground-based and orbiting observatories and laboratories.

The Science Lab Module (SLM) of the Space Station orbiting complex may provide an ideal setting in which to perform certain classes of experiments which form the cornerstone of exobiology research. These experiments could demonstrate the pathways and processes by which biomolecules are synthesized under conditions that simulate the primitive Earth, planetary atmospheres, cometary ices, and interstellar dust grains. For some of these experiments, gravity is a critical factor. Others may require exposure to the ambient space environment for long periods of time. Still others may require on-orbit preparation, servicing, maintenance, fixing, and analysis of samples. The pressurized SLM provides sufficient duration in the space environment and the crew interactions needed to assure implementation of these investigations.

Exobiology experiments proposed for Space Station generally fall into four classes: interactions among gases and grains (nucleation, accretion, gas-grain reactions), novel high-energy chemistry for the production of biomolecules, physical and chemical processes occurring on an artificial comet, and tests of the theory of panspermia. Clearly, many of these simulations contain aspects of interest to the planetary sciences such that a close coupling between these disciplines will maximize science return and promote a more efficient use of resources.

N89-15018

EXPERIMENTAL STUDIES OF CRYSTAL-MELT DIFFERENTIATION IN PLANETARY BASALT COMPOSITIONS

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An important process that controls the evolution of magmas on and within planetary bodies is crystal-melt differentiation. One type of differentiation occurs through the removal of crystalline solids from residual melt by overgrowth zoning, which isolates the crystal interior from reaction with residual liquid. The process of differentiation which accompanies solidification leads to a variation in the composition of magmatic liquids, and contributes to the compositional diversity observed in igneous rocks. It is the dynamic behavior at crystal-liquid interfaces in a solidifying magmatic system that controls the efficiency of this differentiation process.

Experimental studies of silicate melt solidification have been carried out on several planetary and terrestrial melt compositions, and experiments on one of these compositions in the microgravity environment of the Space Station would provide a unique opportunity to understand the factors that control crystal growth and crystal-melt exchange processes at crystal-melt interfaces during solidification. As a crystal-melt interface advances during solidification, diffusion and convection are the two dominant mechanisms by which heat and mass are transferred away from the interface into the advancing liquid. In crystallizing silicate melt systems, convection in crystal-melt aggregates in the vicinity of the crystal-melt interface is generally thought to have only a small effect, but its contribution is unknown. If convection is important, it will homogenize the residual liquid and increase the efficiency of differentiation in residual liquid that can be caused during overgrowth zoning. In the absence of convection, heat conduction away from the crystal-melt interface may become an important factor in controlling the stability and development of the interface. Under microgravity conditions, crystallization can be carried out in an environment where the convective contribution can be diminished, and the diffusive contributions become the dominant controls.

Experimental Requirements:

The experiments would use a chemical system that is thoroughly studied under terrestrial gravity conditions (e.g., Apollo 15 quartz-normative basalts) and redo a selected set of controlled cooling rate experiments in microgravity. These experiments require a furnace similar to the Williams/Lofgren design (see Williams, A System for Conducting. . .This report) which provides the capability to carry out programmed cooling rate experiments under controlled oxygen fugacity conditions. It would also be desirable to have a furnace capable of processing larger volumes of silicate material, up to 50 grams, under controlled cooling rate and controlled oxygen fugacity conditions. This large volume capability would allow study of size-scaling effects of sample surface area and sample volume to nucleation and growth behavior. Again, the microgravity environment provides a unique opportunity to study this effect, since crystals and liquids can be kept from separating by gravity-induced crystal settling. An idea of the magnitude of the effect of changes in the sample volume to surface area ratio on the crystal growth and nucleation behavior is desirable, since the growth rates determined in these experiments are applied to natural magmatic systems which are characterized by large volume to surface area ratios.

The experiments would range from several hours to 50-75 hours in duration, and total experiment time could approach 350 hours. About 20 experiments are required. The experiments would initially be positioned using FePt alloy loops. An extension of the experiment would be application of acoustic positioning techniques. Another desirable modification would be a rotating furnace or experimental charge to counteract even microgravitational effects on crystal-liquid settling over the long durations required for the experiments.

The possibility for on-site examination of some or each experimental charge is desirable. Examination would require the preparation of a thin section or polished surface which would be observed by optical microscopy and scanning electron microscope techniques (an EDS attachment would be desirable). The possibility for on-site examination would optimize planning of succeeding experiments.

N89-15019

KINETICS OF MINERAL CONDENSATION IN THE SOLAR NEBULA

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A natural extension of the type of gas-mineral-melt condensation experiments described elsewhere in this report (Mysen, Crystal-Liquid-Vapor. . .) is to study the gas-mineral-melt reaction process by controlling the reaction times of appropriate gas compositions with silicate materials. In a condensing and vaporizing gas-solid system, important processes that could influence the composition of and speciation in the gas phase are the kinetics of vaporization of components from silicate crystals and melts. The high vacuum attainable in the space station would provide a unique environment for studying these processes at gas pressures much lower than those obtainable in experimental devices operated at terrestrial conditions. Initial experiments would be carried out under static conditions in which the gas phase and mineral or melt would be allowed to come to exchange equilibrium. Further experiments would be carried out at variable gas flow rates to simulate disequilibrium vapor fractionation.

In this type of experiment it is desirable to analyze directly the species in the gas phase in equilibrium with the condensed silicate material. This analytical method would provide a direct determination of the species present in the gas phase. Currently, our notion of the gas speciation is based on calculations from thermodynamic data. These calculated equilibria have not been verified by experiment, and model condensation sequences in the solar nebula make untested assumptions concerning the speciation in the gas phase at various pressures and temperatures. Mass spectroscopic determination of composition and partial pressure in the gas phase would provide this information.

The proposed experiments require similar furnace designs and use similar experimental starting compositions, pressures, and temperatures as those described by Mysen (Crystal-Liquid-Vapor, this report). The proposed experiments are essentially a natural extension of those proposed by Mysen.

N89-15020

SEDIMENT-TRANSPORT EXPERIMENTS IN ZERO-GRAVITY

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One of the important parameters in the analysis of sediment entrainment and transport is gravitational attraction. The availability of a laboratory in Earth orbit would afford an opportunity to conduct experiments in zero-gravity and variable-gravity environments. Elimination of gravitational attraction as a factor in such experiments would enable other critical parameters (such as particle cohesion and aerodynamic forces) to be evaluated much more accurately. A Carousel Wind Tunnel (CWT) is proposed for use in conducting experiments concerning sediment particle entrainment and transport in a space station. The type of wind tunnel we propose consists of two concentric rotating drums. The space between the two drums comprises the wind tunnel test section. Differential rates of rotation of the two drums provides a wind velocity with respect to either drum surface. Rotation of the outer drum provides a "pseudo" gravity ("pseudo" in the sense that a gravity force acts on the particle only when it is resting on the outer drum surface).

In order to test the concept of this wind tunnel design, a 1/3 scale model Carrousel Wind Tunnel (CWT) was constructed and calibrated. In this prototype, only the inner drum rotates, whereas in the final configuration, both drums would rotate at controllable, variable speeds. The outer drum is sealed along its periphery, but there is a small gap between the sides of the inner drum and the outer drum.

Threshold Experiments

Threshold (u_{*_t}) defines the minimum winds required to initiate particle motion and is the fundamental factor in aeolian processes. In the determination of a general expression of the threshold wind speeds for small (~submillimeter) particles, the effect of aerodynamic forces tending to dislodge a particle from a bed of loose granular material is equated to the effect of opposing forces, namely the particle weight (W) and interparticle cohesion (I). The relative magnitudes of these forces have been deduced only approximately from wind tunnel tests of threshold speed (Iversen et al., 1976; Greeley et al. 1980a, Iversen and White, 1982).

The elimination of particle weight in the threshold force equation--as could be accomplished by conducting experiments in a weightless environment--would enable a more accurate assessment of the other factors. The equation of equilibrium for a small particle at threshold is

$$Da + Lb + M = Ic + Wb \qquad (1)$$

Where D, L, and M are aerodynamic drag, lift, and moment, respectively, W is particle weight, I is cohesive force, and a, b, and c are distances from lines of action of the forces to the overturning point. Elimination of the weight term would aid in the determination of the form and magnitude of the cohesive force term at the moment of threshold.

All of the previous experiments have been conducted under conditions of Earth's gravity. It would be extremely valuable to extend the matrix of experiments to include values of artificial gravity above and below that experienced on Earth. This could be accomplished in CWT by placing a bed of particles on the inner surface of the outer drum and rotating the outer drum at different rotational speeds. The rotating outer drum provides an acceleration directed radially outwards, normal to the surface, thus creating artificial gravity. While rotating the outer drum at a constant rate to maintain a constant value of artificial gravity, the inner drum speed can be changed to increase the value of outer-drum wind-friction speed until the top layer of particles leaves the surface at which point the threshold wind friction speed can be ascertained.

Zero-gravity threshold experiments are valuable because of the elimination of the weight term in Equation (1). These experiments would be conducted by rotating only the inner drum, accelerating its speed until threshold is reached.

CWT Flow Characteristics

A series of experiments was conducted in a prototype carousel wind tunnel (CWT) to determine the flów properties. Taylor in 1935 hypothesized nearly potential flow between concentric rotating cylinders with the exception of boundary layers (governed by Prandl's mixing - length theory) near the outer and inner drum walls. Wind velocity profiles were obtained using a TSI Model 1010 hot-wire anemometer. The data show conformity to Taylor's hypothesis and good lateral uniformity of flow. Discrepancies between theory and experiment are due primarily to secondary flows in the wind tunnel cross section which seem to be concentrated near the inner drum. The flow is close to the desired two-dimensionality. Turbulence levels of 6% to 10% were measured within the inner and outer boundary layers. In CWT it is important that the mixing-length theory govern the boundary-layer flow adjacent to the curved cylinder wall surfaces because the same theory governs the flow adjacent to a plane surface and would be comparable to natural conditions and to conditions used in previous threshold experiments (Greeley et al., 1976, 1980b; Iversen et al., 1976). Experiments were performed in CWT to ascertain if these assumptions are correct and if Taylor's hypothesis is valid. For cases in which only the inner cylinder rotates (as in the prototype CWT) and assuming that the surfaces of the cylinder walls are aerodynamically smooth, the following equations for the flow between two infinitely long cylinders can be derived:

inner layer (Prandtl boundary layer)

$$U = R_i\omega - u_{*_i}\{2.5 \ln [(r - R_i)u_{*_i}/\nu] + 5.5\}$$

$$\text{for } R_i/R_o + (\nu/u_{*_i}R_o)e^{0.4R_i\omega/u_{*_i}} < r/R_o < r_2/R_o \qquad (2)$$

central layer (potential inviscid layer)

$$U = KR_i\omega R_o/r$$

$$\text{for } r_2/R_o < r/R_o < r_1/R_o \qquad (3)$$

<u>outer</u> <u>layer</u> (Prandtl boundary layer)

$$U = u_{*_o} \{5.5 + 2.5 \ln [(1 - \frac{r}{R_o}) R_o u_{*_o}/\nu]\}$$

$$\text{for } r_1/R_o \leqslant r/R_o \leqslant 1 - 0.1108/(R_o u_{*_o}/\nu) \qquad (4)$$

Preliminary results show uniform flow and boundary layer properties that are in agreement with theory. Experiments were conducted in the prototype to determine the feasibility of studying various aeolian processes and the results were compared with various numerical analyses. Several types of experiments appear to be feasible utilizing the proposed apparatus.

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N89-15021

DESIGN AND CALIBRATION OF THE CAROUSEL WIND TUNNEL

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In the study of planetary aeolian processes the effect of gravity is not readily modeled. Gravity appears in the equations of particle motion along with inter-particle forces but the two terms are not separable. A wind tunnel that would permit variable gravity would allow separation of the forces and aid greatly in understanding planetery aeolian processes.

Wind tunnels suffer from several shortcomings in aeolian experiments, primarily due to limitations of size. The flow Reynolds Number is a function of the distance from the tunnel entry and for most experiments a long distance is desirable to obtain a sufficiently high Reynolds Number and corresponding fully developed turbulent boundary layer.

A uniquely designed carousel wind tunnel allows for a long flow distance in a small-sized tunnel since the test section is a continous circuit. It also allows for a variable psuedo gravity.

The carousel wind tunnel consists of two concentric drums, the space between the drums being the test section. A wind is generated by rotating the inner drum, which causes a velocity gradient in the air between the drums. This velocity is large enough to initiate movement of sand particles.

A prototype design has been built and calibrated to gain some understanding of the unique characteristics of the design and the results are presented. This prototype does not incorporate the variable psuedo gravity feature, but the design for this aspect is discussed. It is proposed to install this wind tunnel in the NASA KC135 aircraft used for zero g experiments. By comparing the velocity required to initiate saltation threshold at earth gravity, near zero gravity, and at or near 2g's we will be able to make an initial assessment of the effect of gravity on saltation threshold. It will also give us experience in working with this type of tunnel in variable gravity fields.

The experiment will be done in the following manner: A small quantity of sand of a given size will be placed in the test section. The inner drum will be brought to a speed below that required for particle threshold. The bed will be observed as the aircraft begins its manuever to reduce the apparent gravity and the gravity force at threshold will be recorded. This experiment will be repeated at different inner drum speeds and thus a curve of gravity force vs. particle threshold speed will be obtained. When the aircraft is performing its recovery manuever the gravity force will approach two g's. By observing the gravity level at which particle movement ceases for various inner drum speeds the relationship between particle movement and gravity force can be extended above 1 g.

Calibration was performed in the following manner: Using a photo-tachometer to determine drum speed, the drum RPM was correlated with the output from a magnetic pickup sensor displaying a digital readout proportional to drum speed. A TSI hot wire anemometer system was then used to obtain velocity profiles between the drums at five locations between the end walls. This was done for a "large" drum and a "small" drum, The large drum is two thirds the diameter of the outer drum and the small drum, is one-half the diameter of the outer drum. Having examined the data it has been determined that the large drum is more suitable for threshold experiments, while the small drum is better for examining particle trajectories. These data are presented as the ratio of the wind speed obtained to the rim speed of the inner drum vs. the percentage of distance to the outer drum. RMS values of the velocity fluctuations were also taken at selected locations to determine the turbulence level.

Tests were performed using sand of various sizes and thresholds were determined under laboratory conditions. These will be used as a data base to compare the flight data against.

In the final version of this tunnel both the inner and outer drums will rotate. This type of tunnel would be most useful in a zero gravity environment. It will permit a psuedo-gravity effect to be induced,i.e., by rotating the outer drum the particles will be held to the surface by centrifugal force while in contact with the drum. The movement of the drums can be so coordinated that a particle could lift off and return to the surface at the same spot or any chosen location. This would allow some interesting experiments that would shed light on the orgin and development of aeolian ripples and other bedforms.

N89 - 15022

DEVELOPMENT AND TESTING OF A UNIQUE CAROUSEL WIND TUNNEL TO EXPERIMENTALLY DETERMINE THE EFFECT OF GRAVITY AND THE INTERPARTICLE FORCE ON THE PHYSICS OF WIND-BLOWN PARTICLES

R.N. Leach[1], R. Greeley[1], B. White[2], J. Iversen[3].

In the study of planetary aeolian processes the effect of gravity is not readily modeled. Gravity appears in the equations of particle motion along with the inter-particle forces but the two are not separable. A wind tunnel that permits multi-phase flow experiments with wind blown particles at variable gravity has been built and experiments have been conducted at reduced gravity. The equations of particle motion initation (saltation threshold) with variable gravity were experimentally verified and the interparticle force was separated.

Wind tunnels suffer from several shortcomings in aeolian experiments, primarily due to limitations in size. The Reynolds Number that most strongly affects saltation threshold is based on the distance from the tunnel entry, and for most experiments a long distance is required to obtain a suffeciently large Reynolds Number to obtain the corresponding fully developed turbulent boundary layer.This presents a problem, especially when the equipment is to be flight or space borne.

A uniquely designed Carousel Wind Tunnel allows for the long flow distance in a small sized tunnel since the test section is a continous loop and develops the required turbulent boundary layer. The Carousel Wind Tunnel consists of two concentric drums with the test section being the entire space between the drums. Differential rotation of the drums causes an air flow between the drums which entrains particles placed there. Rotation of the outer drum produces a pseudo gravity force holding the particles to the surface in the same manner that gravity does. The force is psuedo in that the particles feel the force only while in contact with the surface. The tunnel is to be used in a micro gravity environment such as on the space station or in the shuttle.

A prototype model of the tunnel where only the inner drum rotates has been built and tested in the KC 135 "Weightless Wonder IV" zero g aircraft operated by NASA Johnson Space Center. Thus for these tests the gravity level was changed by the external environment rather than by the rotation of the outer drum. Reduced or zero g is obtained when the aircraft, after obtaining a suitable excess airspeed, climbs at a 45° angle and then enters a parabolic or nearly parabolic trajectory which produces the reduced or zero g for up to 30 seconds, Figure 1. The aircraft is able to fly 40 or more such trajectories in a single flight.

The wind tunnel, Figure 2, is built of clear polycarbonate plastic and the inner drum is made to spin by means of a variable speed fractional horsepower electric motor connected through a belt drive. The outer drum is 60 cm in diameter and 30 cm wide. The inner drum is 40 cm in diameter and is sized to provide a close fit along the side walls. There is a removable panel in the lower side wall for inserting and removing aeolian test material.

The drum speed is monitored by an AC voltmeter driven by a inductance pick-up which is energized by a magnet attached to the motor shaft. This is correlated with the actual drum rpm as determined with a photo-tachometer. A gravity meter utilizing a sensitive accelerometer displays the gravity level . The rpm, gravity level and particle motion are recorded by video camera during the tests for later analysis. The tunnel is mounted on a stand bolted to the floor of the KC 135.

The experiments were done in the following manner: a small quantity of aeolian material was placed in the test section and the inner drum was spun at a speed below that which would cause any particle movement. As the aircraft entered its maneuver the gravity level at which saltation threshold occured was recorded along with the drum rotation speed. The aircraft did both zero g and low g manuevers ranging from 0.05 tO 0.5 g. By varying the drum rotation speed for subsequent manuevers a matrix of data points were obtained. Often the drum speed was either too high so that a speed much above threshold was obtained or too low so that no particle movement took place. The drum speed could not be changed rapidly enough to to adjust the speed during a maneuver, however as the flights progressed experience allowed a better choice of initial drum rotation speed, obtaining values closer to saltation threshold. The video tape was analysed after the flight so that data obtained even on those maneuvers that exceeded threshold could be used by noting the momentary g level at which particle movement began. The test data were plotted and a reference line drawn through the minimum velocity where saltation occured, Figures 3 & 4.

Data were obtained for two sizes of material. Closely graded ground walnut shells with median diameters of 700 and 1080 microns were used in the two experiments conducted. Walnut shell were used instead of sand for several reasons: (1) they are not as abrasive as sand and do not scratch the wind tunnel as sand or other material does; (2) there is a great amount of of data on the saltation properties of walnut shell from previous experiments in the MARSWIT facility[4] and (3) walnut shell do not become as highly charged by electrostatics as other material, perhaps due to their moisture content (about 8% by weight).

These data were correlated with the friction threshold velocity at saltation threshold by calibrating the Carousel Wind Tunnel with a series of particles of known friction thresholds as obtained in conventional aeolian wind tunnels, thus giving a curve of u* verses drum rotational speed, Figure 5.

The flight data were corrected for the nominal aircraft cabin pressure of 12.25 psi and the datum points closest to the reference line are presented along with the theoretical curve obtained from the equation

$$u_{*t}^2 = \left(0.0166 \frac{rho_p g D_p}{rho}\right)\left(1 + \frac{0.006}{rho_p g D_p^{2.5}}\right) / \left(1.928 R_*^{0.092} - 1\right)$$

The data correlates well with the gravity term for values of g less than 1, Figures 6 & 7. An attempt was also made to obtain values of saltation threshold from 1.0 g to 1.8 g during the aircraft pullup and pullout maneuvers. This was done by speeding up the drum during the maneuver until saltation occured. The data did not prove satisfactory due to the slow acceleration of the drum mentioned earlier and also due to the fact that there is a lag time between the time that the drum reaches a rotation speed and the time that the air flow reaches a constant value.

The above equation can be written in the form:

$$\text{rho}\ u_{*t}^2 = f(R_{*t})((\text{rho}_p g D_p + (K\ I_p)/D_p^2)).$$

If plots are made of

$$\text{rho}\ u_{*t}^2 \quad \text{vs.} \quad \text{rho}_p g D_p$$

and the interparticle force (I_p) is zero these should go through the origin. These are presented in Figures 8 and 9. It appears that the curves intercept the y-axis at a small positive value, indicating that the interparticle force has been identified and separated from the gravity force for these two tests.

Future work includes further experiments with walnut shell in the KC 135 with sharply graded particles of widely varying median sizes including very small particles to see how interparticle force varies with particle size, and also experiments with other aeolian material.

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[4] Geophysical Research Letters, Vol. 3 no. 8, pp 417-420 Greeley, et.al.

FLIGHT PATH OF KC135 AIRCRAFT

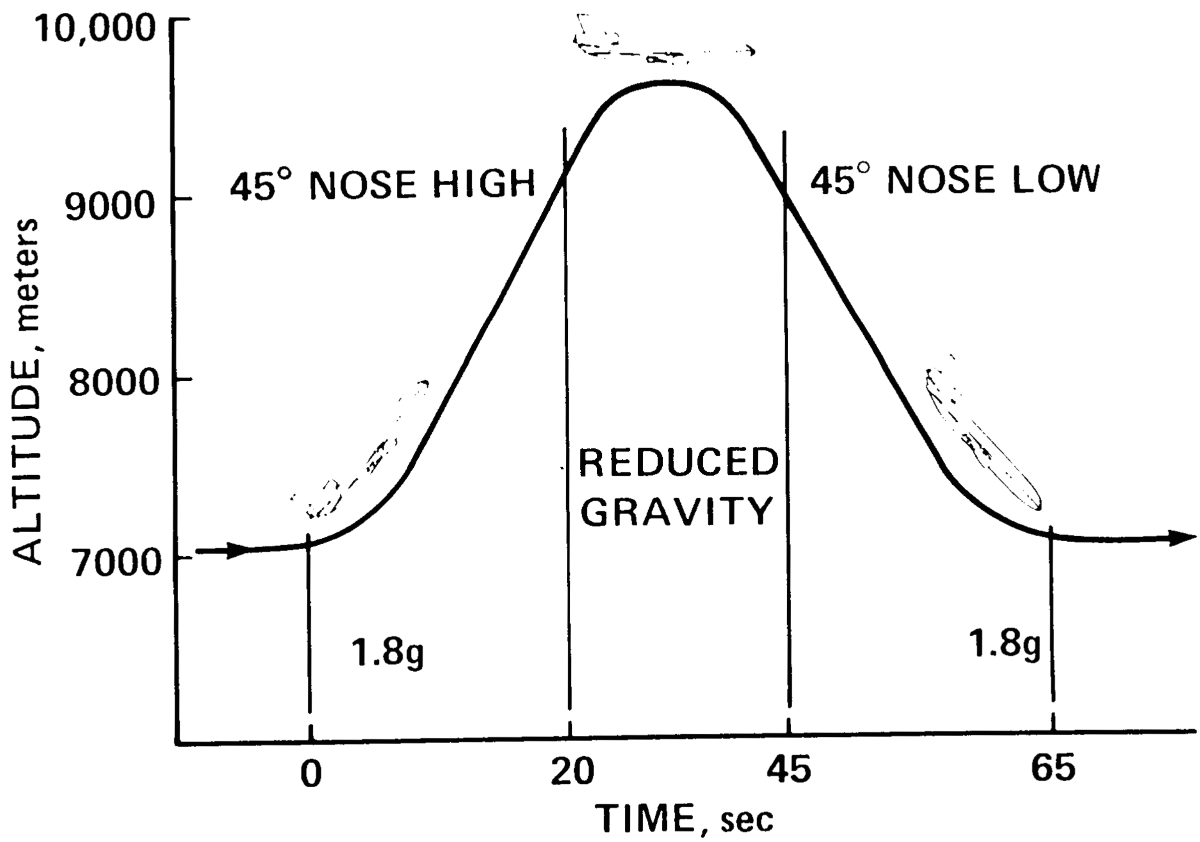

FIGURE 1

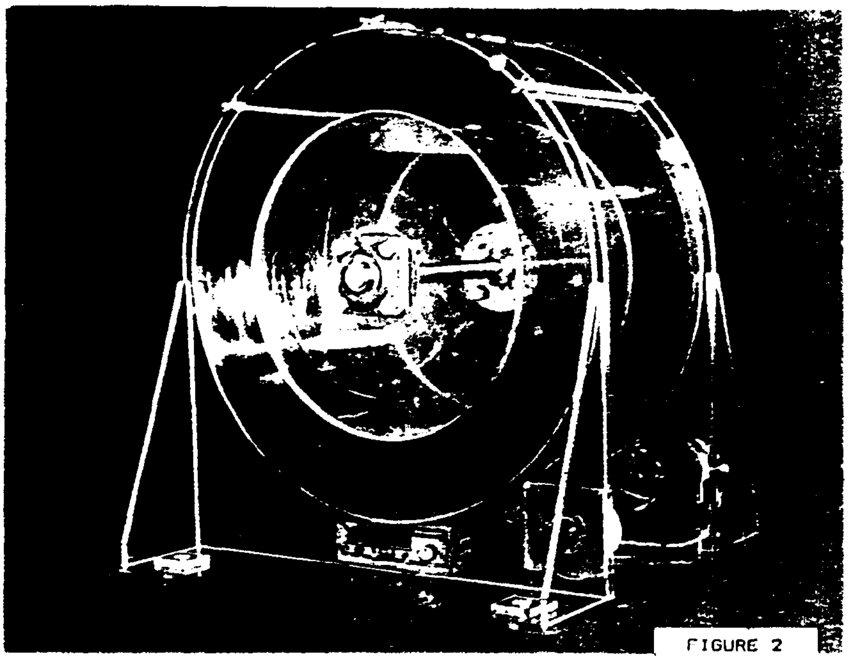

FIGURE 2

RPM SQUARED VS. GRAVITY
1080 MICRON WALNUT SHELL

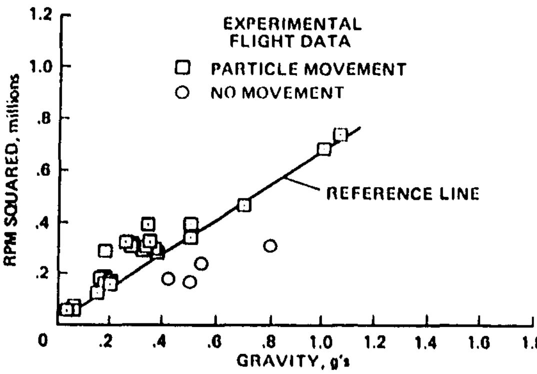

FIGURE 3

RPM SQUARED VS. GRAVITY
700 MICRON WALNUT SHELL

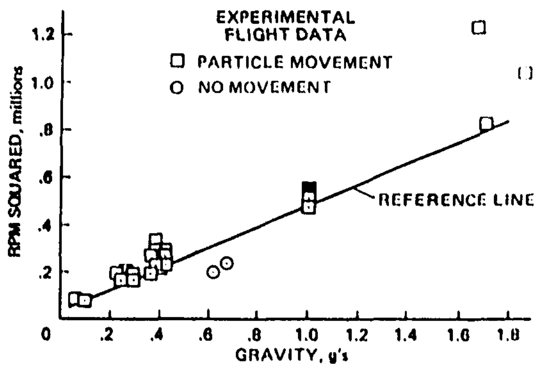

FIGURE 4

μ. CALIBRATION OF CAROUSEL WIND TUNNEL

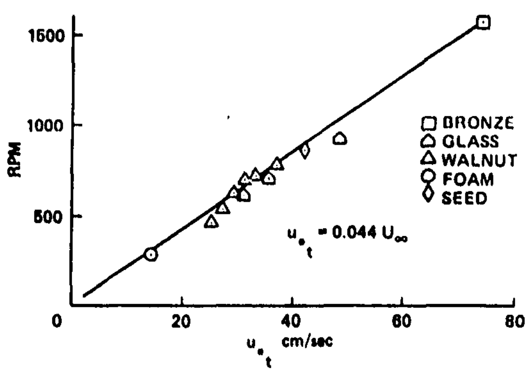

FIGURE 5

FLIGHT DATA COMPARISON
1080 MICRON WALNUT SHELL

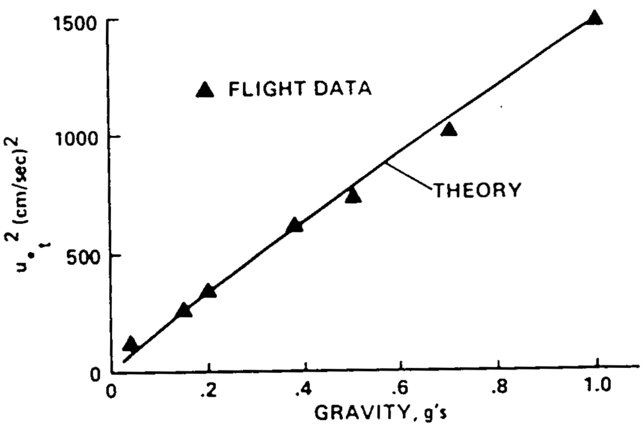

FIGURE 6

FLIGHT DATA COMPARISON
700 MICRON WALNUT SHELL

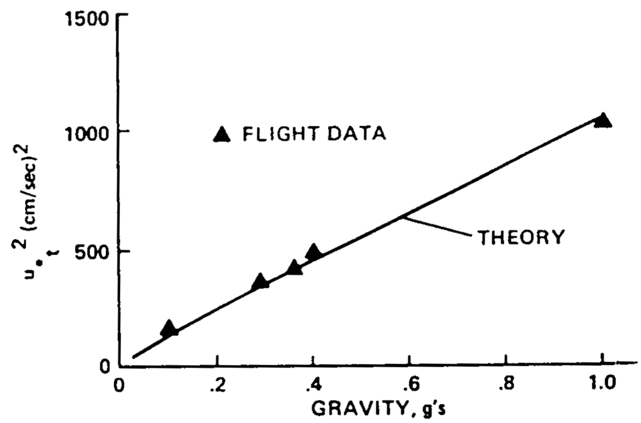

FIGURE 7

FLIGHT DATA COMPARISON
1080 MICRON WALNUT SHELL

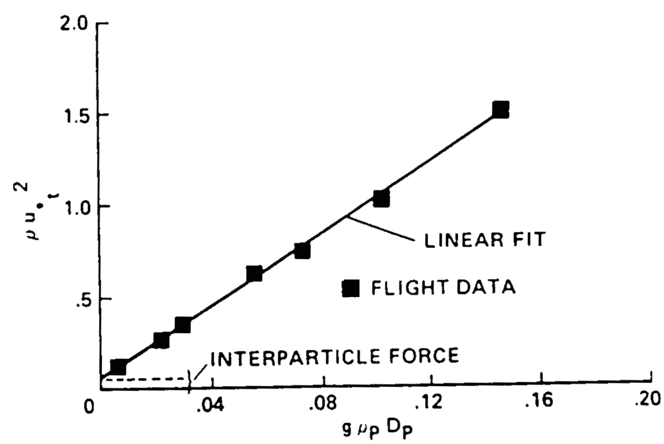

FIGURE 8

FLIGHT DATA COMPARISON
700 MICRON WALNUT SHELL

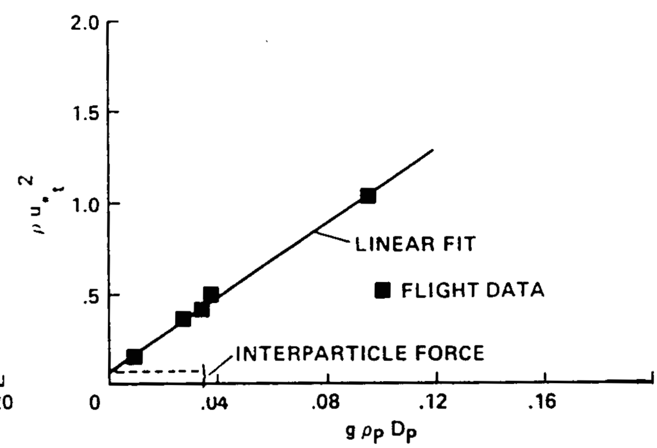

FIGURE 9

N89-15023

DYNAMIC CRYSTALLIZATION EXPERIMENTS ON CHONDRULE MELTS IN REDUCED GRAVITY

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Background

Chondrules crystallized during the earliest formational history of our solar system; and, if crystal settling and flotation are indicators of crystallization in the presence of gravity, they formed without the influence of gravity. In fact, attempts to duplicate the crystallization history of chondrules in the laboratory have met with limited success, because of the difficulty of comparing objects formed under the influence of gravity with objects that did not. These comparisons are difficult because there are several recognized features introduced by the presence of gravity and no doubt some which we do not yet recognize. As a result there are several microscale and macroscale aspects of chondrule petrology which are difficult to understand quantitatively. Most of the features relate to the settling or flotation of early formed crystals; briefly, the major features are:

(1) Chemical gradients set up because nonuniform distribution of crystals isolate phases from the bulk and influence the chemistry of phases which crystallize subsequently.

(2) If the distribution of heterogeneous nuclei is affected by gravity, variations of crystal shape can also occur.

(3) Finally, movement of crystals induces convection-like effects (mixing and flow patterns) in the laboratory experiments which affect the overall texture.

Proposed Experiments

Dynamic crystallization experiments will be carried out in the furnace designed for controlled atmosphere experiments described in this document (see Williams', abstract below). The experiments are designed to look at the effect of reduced gravity on the overall texture of crystallized chondrule melts. The runs will be approximately 24 hrs. long and require maximum temperature of 1400° to $1500^{\circ}C$. The initial experiment would involve heating to the maximum temperature, maintaining isothermal conditions for two hours, cooling at a controlled rate (10° to $20^{\circ}C$/hr.) over the first 200° to $300^{\circ}C$, and then "quenching" by cooling at the natural rate of the furnace by turning the power off. The oxygen fugacities would be maintained slightly above those of the iron-wustite buffer throughout the active phase of the experiment in order to simulate a natural redox state. Three or four charges can be run simultaneously and, thus, the effect of heterogeneous nucleation can be evaluated by varying the composition sufficiently to place the liquidus of some charges above and some below the run temperature. Ground-based experiments would be performed to compare results. A sequence of three or four experiments (each with three or four samples) would be needed to adequately explore the effects of gravity on a relevant suite of compositions. Other experiments such as isothermal crystallization induced by changes in the oxygen fugacity would be investigated in subsequent experiments.

N89-15024

A MAGNETOSPHERIC SIMULATION AT THE SPACE STATION

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It is proposed that a strong magnet (terrella) be flown at or near the Space Station to create an artificial magnetosphere in a "laboratory" setting. The relative flow of the ionosphere past the terrella will constitute a plasma wind that will interact with the magnetic field of the terrella to produce a localized magnetosphere. This object could then be extensively studied using diagnostic probes attached to the Space Station, or with free flyers.

Although small in scale, such a magnetosphere would still be large compared to the gyroradius of the wind particles, as is the case in planetary magnetospheres. On the other hand the β of the plasma wind forming the magnetosphere would be much lower than the β of the solar wind for most planetary magnetospheres. Such a low β MHD interaction would expand the range of magnetospheric observations. In addition, the outside plasma flow is magnetically, rather than dynamically, dominated. This is very different from the earth's magnetosphere where the outside (solar wind) flow is dominated by the dynamic pressure of the flow. The terrella would provide our first example of such a system that we could study.

The support of the Space Station would allow all of the usual benefits to the experimenters of a laboratory; direct access to the experiment, availability of a suite of test equipment, computation and contemplation facilities, rapid turnaround and flexibility, etc. Moreover, the effects of unusual perturbations could also be studied, for example, the introduction of various heavy ions into the system. Another interesting possibility, not seen in planetary magnetospheres, is to charge the terrella to high potentials. Such an experimental setup could therefore do much to advance the general theory of magnetospheric physics.

The space and storage requirements would be minimal, since the experiment would be conducted outside the space station. The total equipment would consist of several terrellas (with varying surface conductivities), ~3 small magnetometer/plasma diagnostic packages, and several gas canisters for upstream "seeding". Power requirements would be ~60 watts. Several track-mounted tethers, each $\gtrsim$ 200 m in length, with the track parallel to the orbital motion and 100 m long, are also needed. Astronaut time needed would be minimal in the tethered configuration (~4 man hours/week). A free-flying configuration, while not needing the tether track, would require much more human interaction.

N89-15025

KINETICS IN A TURBULENT NEBULAR CLOUD

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Model calculations, which include the effects of turbulence during subsequent solar nebula evolution after the collapse of a cool interstellar cloud, can reconcile some of the apparent differences between physical parameters obtained from theory and the cosmochemical record. This turbulent period of solar nebula evolution probably occurred before planet formation (>4.5 Byr ago) and lasted for a period of up to 10^6 years.

Two important aspects of turbulence in a protoplanetary cloud include the growth and transport of solid grains. It is estimated that turbulent coagulation would be a significant process for growth of small grains to ~200 cm sized aggregates during this time period. In addition, grains are in constant association with the remaining nebula gas composition (nominally H:O:C:N ratio of 1000:2:1.2:0.2) and, depending upon the size of the turbulent eddies, may experience grain transport through a significant range of temperatures on time scales between 10 - 100 years. Transport may be inwards to temperatures above the grain sublimation point, to a higher annealing temperature, or, alternatively, towards the cooler outer regions of the evolving solar nebula. Whilst the physical effects of this process (e.g., grain size, rim formation, etc.) can be calculated and compared with probable remnants of this nebula formation period (e.g., primitive meteorites), the more subtle chemical effects on primitive grains and their survival in the cosmochemical record cannot be readily evaluated. Furthermore, experimental conditions pertinent to the chemical formation/alteration of grains in a turbulent protoplanetary cloud cannot be faithfully reproduced using a terrestrial laboratory.

Currently, there is some discussion in the literature regarding the suitability of equilibrium condensation models to explain the unique mineralogy in components of primitive meteorites such as carbonaceous chondrites. This discussion concerns, in part, the apparent difficulty in condensing complex, crystalling refractory phases (including silicates) from a nebula composition gas. An alternative to this problem involves the condensation of simple, amorphous (or partially amorphous) phases which at some later stage (represented in the meteorite record) are transformed through a variety of possible processes to complex crystalline phases. Many current models for the formation of meteorite components also invoke chemical processing of freely-floating grains in a highly reduced nebula composition gas. The unique environment offered by the Space Station (or Space Shuttle) experimental facility can provide the vacuum and low gravity conditions for sufficiently long time periods (days) required for experimental verification of these cosmochemical models.

An example of the type of experiment envisaged would involve a small heating chamber with precisely controlled gas pressures of H, C, O, and N in the range 10^{-1} to 10^{-4} Pa. Micron-sized grains of simple amorphous oxides (e.g., SiO, MgO, FeO, Al_2O_3) would be placed inside the chamber and then annealed at various temperatures (600 K to 1200 K) over a range of time periods. More complex phases such as enstatite ($MgSiO_3$) and/or olivine (Mg_2SiO_4) could also be examined with the C/O ratio varying from nebula (0.6) to >1.0. Samples would then be examined for micro-chemical and structural changes with time using an analytical electron microscope and a range of surface analysis techniques. The fundamental question which would be answered by this type of experiment is: Can complex, crystalline phases (including silicates) form in a nebula gas by the annealing of accreted, amorphous simple oxide grains? Surface analysis of annealed grains would also provide important information on the role of hydrogen in the chemical evolution of these grains via either diffusion or surface adsorption and chemisorption. Reheating specific grains above their sublimation temperature and then recondensing from a hydrogen-rich gas (for various C/O ratios) may also provide a "ground truth" for the temperature effects of turbulent transport on nebula grains.

N89-15026

CAUTIONARY TALES FOR REDUCED-GRAVITY PARTICLE RESEARCH

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Particle experiments conducted by the present investigators on the KC-135 aircraft in zero gravity could be described as having been "less than successful". While such phrasing may be appropriate for scientific journals, the freedom of speech afforded by this abstract enables a more honest appraisal. We report here on tests that were a "total failure". We discuss why this failure occurred, and the sort of questions that potential researchers should ask in order to avoid the appearance of abstracts such as this. Many types of aggregation studies have been proposed for Space Station, and it is hoped that the following synopsis of events will add a touch of reality to experimentation proposed for this zero-gravity environment.

First, however, a word on the motivation for the experiments. Impact cratering, volcanism, and aeolian activity on planetary surfaces inject large quantities of finely-comminuted material into planetary atmospheres. Geological events subsequent to this injection are partially dependent on the degree to which the material aggregates owing to electrostatic and other interparticle forces. Since the material (in the case of impact and volcanism) is freshly comminuted, it should be highly charged electrostatically, and a large measure of aggregation would be expected. However, very little is known about the rate at which this might occur, the level of dust concentration necessary to initiate and sustain significant aggregation rates, how large aggregates may grow, whether or not the aggregation process is selective for certain materials, and whether the structures have sufficient strength to survive their descent to a planetary surface. The answers to these questions would enable conclusions to be drawn about the atmospheric cleansing rate (applicable to such broad concerns as climatic change and nuclear fall-out), the distribution of volcanic ash and aeolian loess, the potential hazards of volcanic surges and pyroclastic flows, the redistribution of wind-blown soils in agricultural areas, and so on.

If aggregation is to be studied for planets that have surface gravitation less than 1g, or if terrestrial cases require prolonged suspension of the aggregates under study, it is essential to investigate the possibility of zero, or reduced, gravity testing. Only under such circumstances can aggregates be prevented from falling to the floor of the experimental apparatus before their behavior has been documented. As a precursor to potential Space Station activities, we conducted aggregation studies both on the ground, and in the KC-135, zero-g aircraft.

Ground experiments consisted of injecting dust into a sealed box with compressed gas. The first discovery was that low concentrations of dust did not show any apparent signs of aggregation, despite the highly charged nature of the dust. Success was achieved however, with high concentrations. Unfortunately, high concentrations do not permit visibility into the central region of interest -- observation becomes limited to the edges of the box where wall-effects are prevalent. Our second discovery concerned the cause of aggregation -- it transpired that particles were more prone to aggregate in the presence of an operator! This was due to the electrostatic field of the human body, and not a result of cooperative materials. There was a marked propensity for aggregation on the walls of the box, and this could not be avoided (these were the largest, and sometimes, the only aggregates). The particles (of basalt dust) were wholly indiscriminate in their choice of surface -- attraction occurred to plastic, glass, wood, paper, rubber, copper, steel, and a host of other materials even after treatment with antistatic spray. An aggregate experiment cannot be conducted scientifically unless wall effects are eliminated, and it must be borne in mind that a Space Station container will be small compared to the electrostatic "reach" of the walls.

Undaunted, we proceeded to conduct experiments on the KC-135 in zero gravity, but to avoid the pitfalls of our ground experiments, only large (1-2mm) particles of charged quartz were used. This would enable visibility through the material, and the wall effects would be less. The particles were injected into the experimental chamber with an air jet, or allowed to fall into the chamber during reduced gravity. This experiment will not work on an aircraft such as the KC-135 if it is anchored, because the zero-gravity parabola is insufficiently stable to retain particles in the center of such a small system. After observing particles on every wall, but not in the center of the box, we concluded that a free-floating experiment would be our only hope (yet to be attempted). Even with relatively stable flying, the experiment failed because it was extremely difficult to <u>disaggregate</u> the particles which perambulated in a clump from one location to another. The air jet did no more than shift the clump from one place to another, as did gentle (and sometimes less than gentle) tapping on the side of the experimental chamber. Aggregation cannot be studied unless the particles are initially dispersed without a great deal of relative motion between the grains. This problem is far from trivial, but it has received very litle attention in Space Station considerations.

We suggest the following for potential investigators of particles in zero gravity: 1) Conduct very extensive investigation of the types of chamber material that will <u>not</u> attract particles. Whatever the chamber is made of, however, the viewing port will probably be glass -- which attracts particles, 2) Determine if the concentrations required for aggregation within the time frame set by 10^{-5}g will allow visibility into the chamber, 3) Find ways of disposing of the test material -- this was found to be a very messy process in zero-g, 4) Determine how surfaces will be cleaned ready for the next investigator. There are materials on the market that can be coated as a liquid (with a brush) onto solid surfaces, and after a few minutes, the material sets as a film that can be peeled away leaving a totally clean surface (developed for the semiconductor industry), 5) Determine how the material will be dispersed initially -- this is absolutely crucial -- any variation in relative velocities will give variation in collision potential, and hence variation in aggregation rates, 6) Be sure that the experiment does not have electrostatic, radiation pressure, or other forces acting spuriously on the material. Is the experiment next to you producing powerful force fields ? Will the astronaut cause aggregation or dispersion when he peers into the chamber ? Does the Space Station laboratory module have its own electrostatic field ? Unless these questions are seriously addressed, a great deal of time and recources could result in one outcome -- an abstract similar to this one.

N89-15027

ELECTROSTATIC AGGREGATION OF FINELY-COMMINUTED GEOLOGICAL MATERIALS

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Electrostatic forces are known to have a significant effect on the behavior of finely-comminuted particulate material: perhaps the most prevalent expression of this being electrostatic aggregation of particles into relatively coherent clumps. However, the precise role of electrostatic attraction and repulsion in determining the behavior of geological materials (such as volcanic ash and aeolian dust) is poorly understood. It may be an important factor in volcanic activity where the size of particles affects the behavior of eruption clouds during ash-fall or pyroclastic-surge, and it may also be important in affecting the threshold, transport, and deposition of aeolian particles. The effect of electrostatics on both pyroclastic and aeolian material could be important on Mars and Venus, as well as on Earth.

Electrostatic aggregation of fine particles is difficult to study on Earth either in the geological or laboratory environment principally because the material in an aggregated state remains airborne for such a short period of time. Also, aerodynamic forces acting on the clusters of particles during precipitation probably affect the aggregation process so that it is impossible to be certain about the respective roles of interparticle forces and aerodynamic forces in any experiment.

Previous studies with finely-comminuted (crushed) geological materials have shown that aggregation occurs very quickly after aerodynamic entrainment, that materials form a variety of aggregation products (one, two, and three-dimensional structures --filaments, flakes, and spheroids, respectively) and that aerodynamic forces during settling apparently modify the rate and nature of aggregation. The experiments also showed that the finest (clay-size) materials of the particulate mass were the primary contributors to aggregates.

Experiments conducted in the NASA/JSC - KC135 aircraft would shed some light on the aggregation process. Zero gravity would allow 1) a brief, but significant, time period for aggregation processes to be studied without settling of material, and 2) an environment in which electrostatic and aerodynamic forces could be separated.

The experimental variables for consideration would be the type of geological material, the method of comminution (aeolian attrition, glacial crushing, volcanic fragmentation, etc.), particle size and shape, and the atmospheric pressure (density) and temperature. The role of time cannot be studied in the KC 135 (except within a ~20 second period) and aircraft experiments are therefore seen as precursors to more elaborate and scientifically more comprehensive Shuttle or Space Station activities. For the KC 135, initial experiments would involve a simple glass case into which a particle cloud could be injected immediately prior to the zero-gravity maneuver. Photography would be the principal experimental record, but a framing rate of ~16 photos per secor would be adequate for preliminary assessment of aggregation. Ir order to prevent contamination of the environment with the particles, the glass experimental chamber would be equipped as standard glove box that would allow the total confinement of sample loading and chamber cleaning between experiments.

Although the proposed experiments are primarily aimed at aeolian and volcanic processes, the information obtained would directly relevant to some of the more recent major issues of "nuclear winter" and the extinction of species in the geologica record speculated to be caused by meteorite impact. Both hypotheses rely upon the role of atmospherically-suspended, finely-comminuted material.

N89-15028

CRYSTAL-LIQUID-VAPOR EQUILIBRIUM EXPERIMENTS AT HIGH TEMPERATURE ($\leq$ 1800^{o}C) AND LOW, CONTROLLED OXYGEN AND HYDROGEN PRESSURE (10^{-1} - 10^{-9} PA)

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Evidence from carbonaceous chondrites points to refractory oxides in the system CaO-MgO-Al_2O_3-TiO_2-SiO_2-Fe-O as being among the earliest phases to condense from the solar nebula (see MacKinnon and Rietmeijer, Condensation Kinetics. . ., This Report). Conversely, in condensation-sublimation models of the chemical evolution of the early solar nebula, the refractory phases will be the last to evaporate. Calculations of the relative mineral stabilities rely on untested assumptions regarding speciation in the gas phase and, sometimes, on less than accurate thermodynamic data for relevant condensed phases (e.g., liquid as well as solid calcium aluminates). It is, therefore, necessary to establish the equilibrium relationships between the relevant crystalline and amorphous phases before the chemical constraints can be meaningfully applied to models of solar system history.

Preliminary experiments on Earth show that such experiments are feasible. These experiments have been conducted on Earth with synthetic diopside and akermanite composition as starting materials. The results indicate that the p_{H2}-temperature conditions governing crystal-liquid, liquid-gas and crystal-gas equilibria might differ substantially from those suggested from calculated models. Lower pressures than attainable in earth-based furnace systems appear necessary. Moreover, incongruent vaporization of both liquids and crystals (leaving a calcium-enriched residue) has been observed.

Condensation experiments from a refractory-oxide containing gas phase in a controlled temperature gradient are highly desirable and can be conducted simultaneously with the phase equilibrium experiments with only minor modification of the presently operating furnace configuration. Finally, a mechanism to analyze the gas phase will provide add information not only to the phase equilibrium experiments but would also provide valuable thermodynamic data about the phases present.

Earth-based experiments suffer from several unavoidable problems. In order to attain controlled, relevant f_{O2} and f_{H2} (with $p_{H2} + p_{O2} = p_{total}$) very high vacuum, not attainable in terrestrial laboratories , is required. Preliminary tests in our terrestrial laboratory with melilite and pyroxene compositions indicate that in order to conduct adequate experiments on these phases as well as on calcium-magnesium aluminates, the ambient pressure should be less than 10^{-11}Pa. This pressure can be reached with the molecular shield technology. Furthermore, even for the best terrestrial vacuum conditions ($\geq 10^{-8}$ Pa), continuous pumping on the system is necessary, thus, rapidly removing gas components. Equilibrium is, therefore, difficult to ascertain. These problems can be overcome by experimentation in the Space Station where the experiments can be conducted under near static pressure conditions and where total pressure equals the sum of controlled hydrogen and oxygen pressures and be controlled for periods exceeding several hours (up to days).

The condensation and fractionation in the early solar nebula occurred as substantially lower gravity than attainable in high-temperature, low-pressure experiments on earth. Microgravity is available in the Space Station, thus, providing a more realistic environment in which to establish the equilibrium relationships.

Finally, terrestrial experiments suffer from container problems where the container may interact chemically with the experimental charge and where the container material can impose an external, unwanted oxygen fugacity. Levitation techniques can provide container-free sample environments, thus, completely eliminating these problems.

Technical Requirements

The experiments require temperatures as high as 1800° C, to be controlled within $\pm 10^{\circ}$C to 1800°C. With the laboratory model, a 5 cm long, 1 cm diameter furnace is used for this purpose. The samples would be 5-10 mg. Power requirements are less than 100 Watts at 110V AC. Because of the low power and high vacuum conditions, thermal insulation is not a problem given the necessary experimental durations (several hours). The furnace is easily adapted to lower-voltage dc power.

Temperature control is accomplished with Tungsten-Rhenium thermocouples interfaced with the temperature control circuit. Hydrogen and oxygen gas pressures are maintained with conventional gas mixing methods. Both the gas pressure , sample change and pressure control can be easily modified for automatic and remote control. Sample-retrieval from, and loading of new, sample carousel every 7-14 days are appropriate. The pressures attainable with molecular shield technology are adequate.

On-site optical and scanning electron microscopic facility (EDS-equipped) are important as are real-time video and data transfer during sample examination. Mass-spectrometer for gas analysis and capability for optical and vibrational spectroscopy is also desirable.

The total volume and weight of the prototype, laboratory-tested model is about 4 kg and 4000 cm^3 (not including the vacuum system). These weight and volume requirements might be reduced further depending on temperature and pressure automation techniques and whether or not an automated sample stage for remote sample insertion and retrieval is implemented.

N89-15029-

THE INITIATION OF GRAIN MOVEMENT BY WIND

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When air blows across the surface of dry, loose sand, a critical shear velocity (fluid threshold, U_{*t}) must be achieved to initiate motion. However, since most natural sediments consist of a range of grain sizes, fluid threshold for any sediment can not really be defined by a finite value but should be viewed as a threshold range which is a function of the mean size, sorting and packing of the sediment. In addition these textural parameters can indirectly affect various interparticle forces such as capillary water tension and electrostatic charges which tend to bend individual grains together, thereby increasing fluid threshold and decreasing the supply of grains to the air stream.

In order to investigate the initiation of particle movement by wind a series of wind tunnel tests was carried out on a range of screened sands and commercially available glass beads of differing mean sizes (range: 0.19mm to 0.77mm), sorting and shape characteristics. In addition, individual samples of the glass beads were mixed to produce rather poorly sorted bimodal distributions. In the wind tunnel tests a sensitive laser monitoring system was used in conjunction with a high speed counter to detect initial grain motion and to count individual grain movements. Test results suggest that when velocity is slowly increased over the sediment surface the smaller or more exposed grains are first entrained by the fluid drag of the air either in surface creep or in saltation. As velocity continues to rise, the larger or more protected grains may also be moved by fluid drag. On striking the surface saltating grains impart momentum to stationary grains thereby reducing the fluid drag necessary for entrainment (dynamic or impact threshold). As a result, there is a cascade effect in which a few grains of varying size, initially moving over a range of shear velocities (fluid threshold range) set in motion a rapidly increasing number of stationary grains. This transition occurs very rapidly and is affected by the sorting, packing and shape of the surface grains. The rapid progression from fluid to dynamic threshold, based on the number of grain movements, can be characterized by a hyperbolic function, the coefficients of which are directly related to the textural characteristics of the initial sediment. The data also indicate that predicted threshold values based on the modified Bagnold equation (Iversen et al, 1976) fall within the range of threshold values defined by the transition section of the grain movement/shear velocity plots. Moreover, the predicted values are very similar to the threshold values derived for the point of maximum inflection on the curves.

NUCLEATION AND PARTICLE COAGULATION EXPERIMENTS IN MICROGRAVITY

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Measurements of the conditions under which carbon, aluminum oxide, and silicon carbide smokes condense and of the morphology and crystal structure of the resulting grains are essential if we are to understand the nature of the materials ejected into the interstellar medium and the nature of the grains which eventually became part of the proto solar nebula. Little information is currently available on the vapor-solid phase transitions of refractory metals and oxides. What little experimental data do exist are, however, not in agreement with currently accepted models of the nucleation process for more volatile materials.

The major obstacle to performing such experiments in Earth-based laboratories is the susceptibility of these systems to convection. Consequently, it has so far proved impossible to controllably nucleate carbon, aluminum oxide, and silicon carbide smokes. Such smokes should be among the first condensates in stellar outflows.

Evaporation of refractory materials into a low-pressure environment with a carefully controlled temperature gradient will produce refractory smokes when the "critical supersaturation" of the system has been exceeded. Measurement of the point at which nucleation occurs, via light scattering or extinction, can not only yield nucleation data but also, information on the chemical composition and crystal structure of the condensate. If optical monitoring is continued, the measurements will yield data on the sticking coefficients of newly formed submicron refractory particles by determining the time evolution of the particle-size distribution. It might also be possible to deposit a volatile mantle over the dispursed refractory cores in order to study the optical properties and the coagulation efficiencies of such core/mantle grains. Optical methods should be supplemented by active particle collection (and subsequent analysis) in order to determine the morphology and degree of crystallinity of the newly formed particles as well as the structure of the core/mantle grains.

Experimental Requirements

Low pressure conditions ($<10^{-6}$ Pa) and cryogenic temperatures together with $\leq 10^{-5}$g are necessary. Total ambient temperature range is 4-400K; crucible temperature range up to approximately 3000K. Power requirements are ~ 100 Amp at 28 volt. Local heating with a CO_2-laser might be required. Total volume is about $4m^3$. Run duration is up to 24 hours. Experiments can be monitored remotely. Real-time video and still photography are required and continuous crew interaction, or the capability for remote control of the experiment from the ground, is preferred. The experiments require on-board facilities for analysis of surface properties, scanning and transmission electron microscopy, and mass-spectrometric analysis. These could be built into the experimental system where the use of on board analytical capability would be impractical.

NUCLEATION EXPERIMENTS IN A MICROGRAVITY ENVIRONMENT

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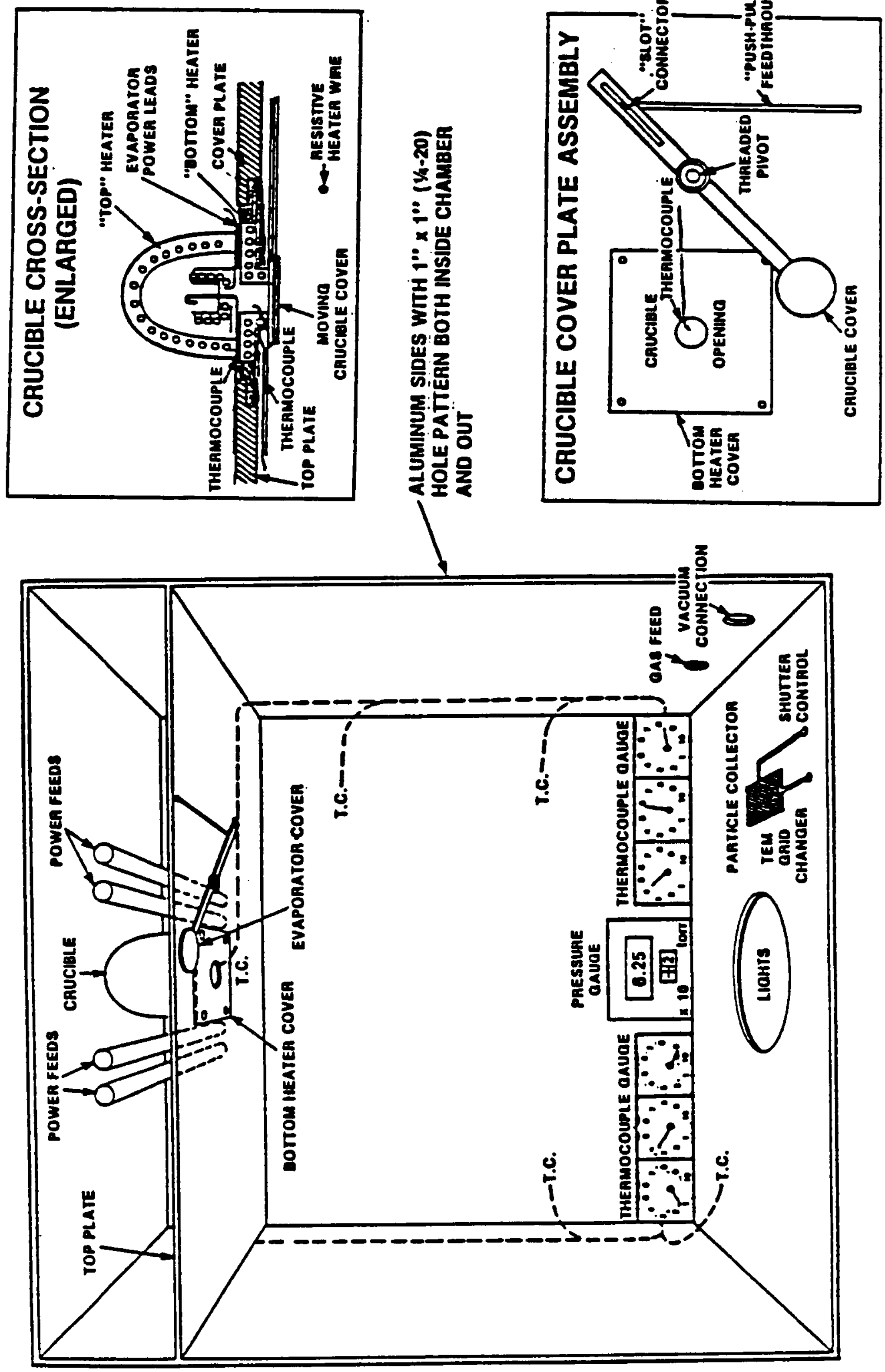
A simple experimental apparatus (Figure 1) will be described in which a wide variety of vapor phase nucleation studies of refractory materials could be performed aboard NASA's KC-135 Research Aircraft. The chief advantage of a microgravity environment for these studies is the expected absence of thermally driven convective motions in the gas. The absence of convection leads to much more accurate knowledge of both the temperature distribution in the system and the time evolution of the refractory vapor concentration as a function of distance from the crucible.

We will describe the evolution of the apparatus as we gain more experience with the microgravity environment. Expected modifications include the addition of a programmable thermal gradient away from the crucible and a dye laser probe coupled with a detector system based either on a reticon array or a series of diodes. This latter system should make it possible to obtain a great deal of information not only on the conditions under which nucleation occurs, but also on the optical scattering and absorption characteristics of the particles produced in the experiments. These particles will be collected for SEM/TEM analysis. Comparison between the experimental results and the predictions of Mie theory for the measured particle size distribution will be made. In addition, an attempt will be made to measure the coagulation coefficient for a variety of materials and particle sizes by monitoring the time evolution of the size distribution.

We expect that a significant amount of nucleation data can be collected using the KC-135; considerably less information will be collected on the coagulation of the particles due to the short period of time in which the data can be obtained. Nevertheless, such experiments will be used to prepare for similar ones carried out aboard either the Shuttle or the Space Station where considerably longer duration experiments are possible.

ORIGINAL PAGE IS
OF POOR QUALITY

FIGURE 1



N89-15031

ULTRAVIOLET SPECTROSCOPY OF METEORIC DEBRIS: IN SITU CALIBRATION EXPERIMENTS FROM EARTH ORBIT

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Introduction. We propose to carry out slitless spectroscopy at ultraviolet wavelengths from orbit of meteoric debris associated with comets. The Eta Aquarid and Orionid/Halley and the Perseid/1962 862 Swift-Tuttle showers would be our principal targets. Low light level, ultraviolet video techniques will be used during the night side of the orbit in a wide field, earthward viewing mode. Data will be stored in compact video cassette recorders. The experiment may be configured as a GAS package or in the HITCHHIKER mode. The latter would allow flexible pointing capability beyond that offered by shuttle orientation of the GAS package, and doubling of the data record. The 1100-3200 A spectral region should show emissions of atomic, ionic, and molecular species of interest on cometary and solar system studies.

A major problem at the present time is an inability to accurately convert observed meteoric spectral intensities into compositional information. This problem could be circumvented and a significant amount of data on fundamental meteoric phenomenon could be obtained by the high-velocity injection of well characterized projectiles into the earth's upper atmosphere. This could be accomplished quite easily if a rail gun were available on the space station as part of the microgravity cratering facility (or for other reasons). Projectiles launched from a rail gun in earth orbit could enter the atmosphere at velocities as high as 25 km/s. Optimal viewing of such artificial meteors could be achieved if the gun and detector systems were located on separate platforms several hundred kilometers apart.

Discussion. Analysis of middle to far ultraviolet spectral data of meteoric debris of cometary origin has yet to be carried out. Objectives of such a study include the observation of many atomic species, both neutral and ionized, including the strong feature due to MgI at 2850A and the strong blend at 2800A due to MgII and MnI. An interesting possible metal emission is that of BeI at 2349A.

Carbon is an expected constituent of comet-associated meteors. Though spectral features can exist in the visible region, carbon cannot be observed due to masking, principally by iron. The 1000-2000A region should be relatively free of FeI and FeII emission allowing observation of CI at 1193A, CI at 1330A, CI at 1561, and CI at 1657A. In addition, strong SiI and SiII emissions exist in the region suggesting determination of the C/Si ratio. Lines of SiO could also be observed at 1310A.

Lyman alpha emission occurs at 1215A due to hydrogen from dissociating H_2O and hydrocarbons. The video technique allows examination of the temporal development of the expected strong Lyman alpha emission from cometary sources. Sulfur lines occur at 1807A and 1820A; phosphorus lines occur at 1672A, 1675A, 1680A, and 1775A. Sulfur is a relatively abundant component of carbonaceous chondrites and its existence in cometary debris is of interest. The recent IUE observations by the Univ. of

UV SPECTROSCOPY OF METEORIC DEBRIS

J. A. Nuth, T. J. Wdowiak, and W. R. Kubinec

Maryland group, led by A'Hearn revealing dimer sulfur (S_2) emissions between 2820A and 3090A of comet IRAS-Araki-Alcock, makes the search for meteor sulfur all the more interesting.

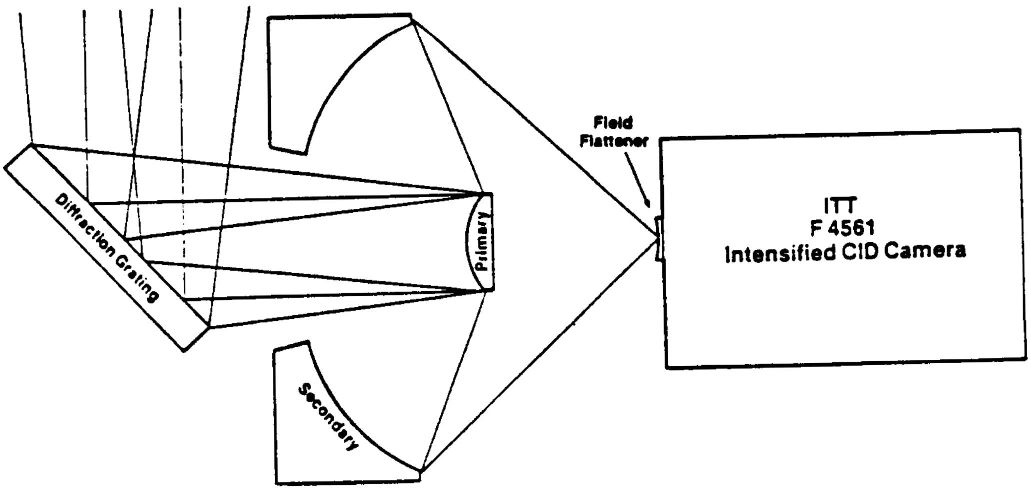
Instrumentation. The experiment makes use of high speed (f ratio of 0.75) reflecting optics viewing a 12° by 12° field with an objective grating. The imaging detector is an intensified solid-state array having the following characteristics:

1100-3200A	6 ma/watt sens. (1500A)
UV intensified CID	20 ma/watt sens. (2500A)
244 x 388 pixels	CsTe/MgF_2 p.c./wind.
8.7 x 11.4 mm	ex. ITT F.4561

The dispersing element would be a 300 l/mm grating blazed for first order with a 250 A MgF_2 protective coating. Fig. 1 displays the proposed optical configuration.

In the GAS configuration, video data will be stored in a stack of up to four compact video cassette recorders. Depending upon recording speed, a total record duration for the four-stack would be eight to twenty-four hours. Because data is recorded for approximately twenty minutes per orbit, data would be gathered over twenty-four to seventy-two orbits. Control would be by microprocessor and total power required would be less than 1.2 KWH from a battery pack of less than 1 ft^3 and 100 lb.

A HITCHHIKER configuration would allow greater volume by utilizing shuttle power and additional GAS type containers for data storage. The optics/detector could then be gimbeled to allow some pointing capability.



N89-15032

LOW-GRAVITY FACILITIES FOR SPACE STATION PLANETOLOGY EXPERIMENTS

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For experimentation, space offers a unique environment which is unobtainable on Earth. One characteristic is a gravity force less than 1 g, where g is the mean Earth gravity acceleration of 9.8 m/s^2.

A near-zero g level is easiest to obtain, since orbiting spacecraft are in free fall. This condition, which is desired for many science and engineering applications, is referred to as microgravity. Total elimination of acceleration is difficult since perturbing forces, such as atmospheric drag, expulsion of mass, and disturbances, will contaminate the gravity environment. The purity of zero g is specified by some level of noise, such as 10^{-4} g; however, no single number can really indicate the true nature of the noise, which may be high frequency, low frequency, or intermittent.

Producing uniform gravity level about zero g in space is quite different than producing microgravity. Here, a constant force must be produced over long periods of time. Thrust may be applied to spacecraft to produce low gravity, but this is not very practical, except perhaps with solar sails. For Earth orbital facilities, two methods are possible: (1) centrifugal force through rotation, or (2) gravity gradient force using long tethers. Which approach should be used depends on many factors, both from the standpoint of user requirements, and from design, implementation, operation and cost considerations. This presentation identifies the major parameters which should be considered in any design. It also presents some basic characteristics of rotating and gravity gradient tethers, and evaluates possible conceptual designs.

For planetology experiments, providing gravity in space will make it possible to more nearly simulate conditions on natural bodies. Its presence may be unnecessary for simulation of comet surfaces, since gravity is of the order of 1×10^{-5} g; however, for other bodies, it may be important. In terms of Earth gravity, the g-levels are:

larger asteroids:	0.01 - 5%
Moon, Io, Titan:	15 - 20%
Mars, Mercury:	35 - 40%
Venus, Saturn, Uranus:	80 - 100%

The types of planetology experiments which may be conducted under these g-levels may be impact, flow transport, and chemical reactions with solids, liquids, or gases. Also, using scaling laws, it may not be necessary to use one-to-one correspondence of the g-level with the planetary body of interest. Very likely, with each experiment, some minimal g-level will be necessary.

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* Section Staff, Mission Design. Written while on a one year assignment at NASA, Office of Space Flight, Advanced Programs, Washington, D.C. The research described in this paper was performed by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

The g-level is but one parameter involved in the design of a specific experiment. Other requirements may be:

1. g-level range
2. g-level tolerance value
3. Coriolis tolerance value
4. Volume requirement
5. g-level duration
6. Power and materials for experiment
7. Automated operation or man-tended

These requirements, and certainly others, will dictate the type of facility which should be considered. At one extreme, the requirements should be modest, and a centrifuge within a manned module may suffice. For example, a one meter radius centrifuge with a rotation period of six seconds will produce about a 10% g-level. The Coriolis effect will be naturally high, and the usable volume small, which may or may not be a problem.

On the other hand, the planetology experiments may be such that they could only be done in a Spacelab environment: i.e., large volume, long duration, man operated, and low Coriolis effects. This may best be done by tethering a manned module from the Space Station; or by a large rotating structure not attached to the Space Station.

The larger facility, manned or unmanned, is the type being considered in this presentation. By the time that the Space Station is in operation, many tether experiments would have been done in space using the U.S.-Italian Tethered Satellite System on the Shuttle. On the second experiment, the Italian subsatellite will be tethered 100 km below the Shuttle. It will experience a g-level of about 5%. A similar tether system could be designed for use on the Space Station.

Concerning large rotating systems, the capability which must be developed for constructing the Space Station itself can be directly applied here. Also, many of the Station subsystems can be used. One configuration might be to have two laboratory modules, one at each end of a long beam structure. A hub at the center of this structure could contain a platform with required subsystems. This could also be an arrival and departure point for crew and supplies. An elevator on the structure could provide transportation from the hub to the modules at the ends.

A structure 200 m long could be set rotating using thrusters at each module. A velocity of 7 m/s would provide a 5% g level. Increasing this to 20 m/s would produce 40%. The periods of rotation would be 1.5 min. and 30 sec., respectively.

Many other configurations are also possible, and a final selection will depend on many factors including user requirements.

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DEBRIS-CLOUD COLLISIONS: ACCRETION STUDIES IN THE SPACE STATION

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<u>Background</u>: The growth of planetesimals in the Solar System reflects the success of collisional aggregation over disruption. It is widely assumed that aggregation must represent relatively low encounter velocities between two particles in order to avoid both disruption and high-ejecta velocities (1,2). Such an assumption is supported by impact experiments (3) and theory (4). Experiments involving particle-particle impacts, however, may be pertinent to only one type of collisional process in the early Solar System. Most models envision a complex protoplanetary nebular setting involving gas and dust. Consequently, collisions between clouds of dust or solids and dust may be a more realistic picture of protoplanetary accretion. Recent experiments performed at the NASA-Ames Vertical Gun Range (5) have produced debris clouds impacting particulate targets with velocities ranging from 100 m/s to 6 km/s. The experiments produced several intriguing results that not only warrant further study but also may encourage experiments with the unique impact conditions permitted in a microgravity environment.

<u>Collisions Between Debris-Clouds and Particulate Surfaces</u>: Impact experiments at the NASA-Ames Vertical Gun Range have assessed differences between clustered and single-body impacts on particulate surfaces. The primary goal was to examine the effects of atmospheric entry on cratering and possible implications for secondary cratering processes (5). Impacting debris clouds were produced during passage of a brittle pyrex projectile through a thin sheet of paper or aluminum foil. At hypervelocities ($v > 5$ km/s), a 2.5 mil sheet of paper was sufficient; at supersonic velocities ($v \sim 2$ km/s), a 1 mil aluminum foil was used. Because the launch tubes are rifled in order to induce separation between the projectile and sabot, the effective dispersion of the debris cloud could be varied by changing the distance between the target surface and paper or foil. High-frame rate photographs recorded the resulting dispersion in the impacting debris cloud and thus the effective density at impact.

The experiments revealed a factor of 5 decrease in predicted cratering efficiency for an impact by a solid projectile of the same mass (m) and velocity (v). If the energy density of the impacting cloud is included (6) by using a dimensionless expression of cloud radius (r) divided by v^2, then cratering efficiency is only slightly decreased. As might be expected, the crater aspect ratio and morphology were significantly altered (5). As typical for laboratory experiments, however, several unexpected phenomena also occurred. First, the high frame-rate photographic record revealed an intensely luminous cloud immediately after impact (7). The early stages of ejecta-plume growth were characterized by an amorphous cloud rather than the systematic expansion of a funnel-shaped curtain typical for single-body impact. Second, unusually large (1-5 cm across) fairy-castle aggregates were produced. Many of these aggregates had low-ejection velocities. An impact by a 0.2 g/cm^3 cloud at 4.1 km/s produced an unusually large aggregate extending from the floor to above the crater rim. The exact nature of such aggregates is not yet known; they appear to be melt-welded target material. We also do not yet know for certain if melt production increased relative to a single-body impactor. The early-time film record showing a bright luminous cloud and the slight decrease in cratering efficiency, however, may be indicating greater partitioning into internal energy losses. These preliminary results would indicate that collisions between two debris clouds might produce aggregates, thereby increasing particle sizes, whereas a single particle impacting a particle results in disruption and comminution. Such an experiment could provide new insight for early planetary growth processes and for interpreting the record of this stage (e.g., 8,9).

Possible Space Station Experiments: The microgravity environment of a Space Station would allow detailed studies of the competing processes of aggregation and disruption using conditions more appropriate (or at least scalable) for an evolving protoplanet. A cloud of impactor fragments can be readily produced in a manner already performed on Earth, but of different density, composition, and initial size distribution. Of specific interest would be the change in size distribution, shock state, velocity distribution, mixing, and the possible production of chondrite breccias (10). The formation of chondrules is more equivocal (10) but objections could reflect an incomplete experimental simulation. Collisional velocities would range from values expected for collisions in a nebular disk (< 100 m/s) to values possible from the early stages of planetesimal growth (<6 km/s). Perhaps the most intriguing aspect is the capability of repetitive collisions and more unusual conditions, e.g., passage of a larger projectile through a suspended debris cloud. The latter experiment could be performed over long path lengths by tubular extensions from the proposed impact facility.

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N89-15034

IMPACTS OF FREE-FLOATING OBJECTS: UNIQUE SPACE STATION EXPERIMENTS

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The transfer of momentum and kinetic energy between planetary bodies forms the basis for wide-ranging problems in planetary science ranging from the collective long-term effects of minor perturbations to the catastrophic singular effect of a major collision. In the former case, we can cite the evolution of asteroid spin rates and orientations (1,2,3,4)) and planetary rotation rates (5). In the latter case, we include the catastrophic disruption of asteroids (3,6,), sudden but lasting changes in planetary angular momenta (7,8), and the near-global disruption of partially molten planets (9,10). Although the collisional transfer of momentum and energy has been discussed over the last two decades, major issues remain that largely reflect current limitations in earth-based experimental conditions and 3-D numerical codes. Two examples with potential applications in a Space Station laboratory, are presented below.

Asteroid Spin Rates and Orientations: Understanding the transfer of impactor translational momentum to target angular momentum is fundamental to understanding the present-day spin rates, orientations, and spin-limited disruption of asteroids (e.g., see 3). The efficiency of angular momentum transfer is typically expressed as a factor (ζ) ranging from 0 for purely elastic collisions to 1 for inelastic collisions with no ejecta loss (3). Although ζ is usually adopted as unity, Harris (4) prefers a value closer to 0.5 corresponding to a moderate forward-scattering of ejecta. Davis *et al.*, (3) suggest that ejecta are uniformly distributed -- even for low-angle impacts; consequently values of ζ closer to 1 might be justified. Such estimates, however, are largely based on intuition. For vertical impacts into basalt, ejecta carry away 4-6 times the original impactor momentum; therefore, the azimuthal distribution of these ejecta is crucial. For very low-angle impacts, the impactor is ricocheted down-range and carries with it considerable momentum (11). These results would indicate a value of ζ significantly less than 1. Even lower values may occur for curved surfaces. Recent experiments in easily volatilized material (12) reveal significant differences in the partition of energy at low-impact angles. Such differences might lead to differences in impact-induced spin rates between comets and asteroids (13).

Thus a wide range of values in ζ that depend on impact velocity and target composition/strength can be justified. Experiments are needed wherein free-floating non-spinning and spinning objects of varying strength, porosity, volatility, and strength are impacted at varying impact velocities and angles. A Space Station provides a unique and ideal environment for performing such experiments.

Planetary Disruption/Spin-Rates: The existing rotation periods and total angular momenta of gravitationally bound planets and planet-satellite systems may provide a fundamental link between the accretion and post-accretion stages of planetary evolution. The Moon and Mercury preserve a record of impacts of sufficient energy to produce possible antipodal disruption of the surface as indicated by observations and simplified calculations (9). More sophisticated 2-D axisymmetric finite-element codes reveal that a molten interior enhances disruption.

Taken to extreme, a collision-vaporization model of the Earth-Moon system has been recently revived with vigor and substance (14,15). Although preliminary calculations have been made to describe the impact-induced vaporization of the early terrestrial crust and the transfer of angular momentum (16), such models are limited by necessary simplifying assumptions including 1-D and 2-D descriptions of a 3-D event. It is unlikely (albeit fortunate) that a directly scaled event will occur. A space station platform, however, provides a unique opportunity to test important facets of such models by allowing freely suspended spherical targets of varying viscosities, internal density gradients, and spin rates. Although a centralized gravity term cannot be introduced or completely simulated, such limitations are far outweighed by variables that can be readily introduced and controlled.

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N89 - 15035

HOW TO MAKE A COMET

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The primary mandate of NASA is the study of the nature and origin of the solar system. The study of comets provide us with unique information about conditions and processes at the beginning of the solar system. Short period comets and their relatives, the near Earth asteroids may prove to be second only to the sun in importance to the long term survival of civilization for two reasons. They are a possible candidate for the cause of mass extinctions of life on Earth; and they may provide the material means for the expansion of civilization into the solar system and beyond. They almost certainly represent the most primitive material of the solar system, still tantalizingly unavailable until space craft bring us first-hand information. In the meantime we must study comets by remote means. Laboratory investigations using synthetic cometary materials may add to our knowledge of these interesting objects.

Comets are presumed to be made of ices with noncontacting dispersions of micron and sub-micron sized particles (Whipple, F.L., Ch.1, Comets, page 67 in McDonnell.J.A.M., Cosmic Dust, New York, NY, Wiley & Sons, 1978). The most difficult physical characteristic to simulate is the dispersion of particles in ice in a way that prevents them from touching one another. This requirement is crucial because if the particles touch one another they are unlikely to be separated by the fluid dynamic forces (or electrostatic forces) at the subliming ice surface and the observed free flowing dust plume (comprising the comet's tail) will not be possible. It is possible, however, that even if the particles are not touching in the ice they may not escape the subliming surface and thus may form a mantle under some low rate of solar insolation. It is the study of these two processes, dust and mantle formation, that is the objective of this ongoing laboratory experimental investigation.

* C-3

ORIGINAL PAGE IS
OF POOR QUALITY

If a dispersion of particles in liquid water is frozen by ordinary means the freezing ice crystals push the particles ahead of the freezing solid-liquid interface. The particles are trapped in the ice where the ice crystals collide with one another. In the materials purification industry this phenomenon is referred to as zone refining. This phenomenon must be avoided if particle contact is to be prevented. In synthesizing comet ices we tried several methods of high-speed freezing the liquid dispersions of particles to obtain the requisite noncontacting particle dispersions in ice.

The most reliable means of freezing required that we spray a very dilute dispersion (100:1) of montmorillonite clay in water into liquid nitrogen through a very small nozzle (< 10 microns) at high pressures 500 psi). The nozzle must be within a few milimeters of the surface of the liquid nitrogen so that the droplets hit the liquid at high velocity and are frozen quickly. Because the orifice is nearly as small as the particles, means must be provided for continuously unplugging the nozzle. This was accomplished by using an adjustable coaxial needle valve orifice that could be continuously vibrated to remove any plugs produced by the submicron montmorillonite clay particles.

A slurry of water ice particles was formed in the liquid nitrogen. The liquid nitrogen was decanted and the concentrated slurry was poured into two stainless steel hemispherical salad bowls. A fine wire thermocouple was inserted into a small hole in the center of one hemisphere of the consolidated slurry. The other hemisphere was then joined to the first to form a spherical body of weakly sintered ice particles.

This "snow ball" (0.3 gm/cm3) was then suspended in a fine nylon hair net from a small spring scale. The entire assembly was then hung inside a cryotrapped, diffusion-pumped high-vacuum chamber. The chamber was pumped down to (10 -4 Torr) before all of the absorbed liquid nitrogen evaporated. The thermocouple indicated that some of the liquid nitrogen was in fact frozen during pumpdown.

This miniature "comet" sublimed away its water ice over the next seven days while the vacuum pressure, ice temperature and the weight of the body were recorded periodically. At the end of the experiment the sublimate residue that was left formed a sphere nearly the same size and shape as the original snow ball (.009gm/cm3).

Three slightly different "comet" sublimation experiments were performed in which the dust compositions (graphite was added) and concentrations (500:1) were varied. The sublimate residue spheres formed were similar in most respects (the 50% graphite made a weaker gray residue). They all took 7 to 8 days to sublime completely. The lowest temperature recorded after the solid nitrogen had sublimed was in the range of -60^{0} C. The ice probably reached lower temperatures near the end of the experiment but, because the thermocouple lead conducted a significant amount of heat into the ice body the ice probably sublimed away from it early in the experiment. The vacuum chamber pressure continued to drop during the sublimation period (final pressure was 10-7Torr). This indicates that as the sublimate residue became thicker its insulating properties increased and the ice temperature dropped thus reducing the water vapor pressure in the chamber.

During the pumpdown small pieces (< 1 mm) of ice were ejected from the surface of the spherical body. These pieces of "snow" sublimed very quickly once they came in contact with the room temperature floor of the vacuum chamber. No indication of any free dust coming off the ice or from the sublimate residue was observed. The 300K walls of the vacuum chamber apparently did not produce enough radiation load onto the ice to produce a dust plume or the dust plume was so tenuous that we could not observe it. Future experiments using a solar simulator may be able to produce dust plumes. Some form of nephelometry will be used in these subsequent experiments to observe the dust if it is released. The amount of electrostatic charging produced due to the sublimation and the effect of induced electrostatic charge will also be measured.

N89-15036

VOLATILIZATION-FRACTIONATION OF SILICATES RELATED TO CHONDRITE COMPOSITION

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Background

The compositions of chondritic meteorites are linked to the solar composition. It is believed that the chemistry of the (generally) drop-shaped chondrules which comprise a large portion of these meteorites may present valuable clues to their formation and, ultimately, to the early conditions and processes of the planets. A prime candidate mechanism linked to compositional variations in chondrules is vapor fractionation involving either the volatilization of silicate, sulphide, oxide, and metal phases or the reverse processes, condensation from a nebular or stellar gas. Thermodynamic models of these processes exist and, fairly recently, a body of experimental data have been acquired with which to test these and related models of chondrite and planet formation (Mysen et al. 1985).

Experimental Objectives

The purpose of this experiment is to determine the nature of volatilization-fractionation of silicate (and related metallic) compositions related to chondrite compositions. This would be accomplished at ambient (i.e., probably 10^5Pa) pressure at temperatures from 1500^{o}C to 2200^{o}C, at partial pressures of oxygen varying from 10^{-9} to 10^4Pa and as a function of the bulk composition of the silicate starting materials. In addition, vapor fractionation from individual silicate liquid droplets will be studied as a function of droplet size. The rate of volatilization is expected to be a function of the surface-volume ratio and, therefore, is a function of droplet size. If found, this relationship can in turn be related to conditions required by several models of chondrule formation.

Experimental Conditions in Terrestrial and Space Environments

The minimum temperature at which volatilization of major elements in these systems can effectively be studied is about $1200^{\circ}C$. At these temperatures, such experiments must be carried out at reduced pressure (i.e., around 10^{-1}Pa or lower). In order to achieve significant volatilization rates at atmospheric pressure, temperatures of around $2200^{\circ}C$ are required. Volatility of many of the phases of interest is a strong function of oxygen pressure and, consequently fugacity must be controlled within the range from 10^{-9} to 10^{4}Pa. The foregoing conditions can be met rather easily in earthbound experiments. However, one major problem cannot be addressed sufficiently for the purposes of the experiment: the container problem. On Earth it is necessary to place the sample in a container. The problem is that, at the required temperatures, all container materials either react with the samples (e.g., silicates react with ceramics or metals with metallic containers) or they impose their own oxidation conditions on the run (as with tungsten). These major problems are immediately and totally removed in the space environment where a container is unnecessary. Preventing gravitational separation of phases which may have quite different densities is another major problem in the terrestrial environment. It is virtually impossible, for example, to maintain intimate mixture of silicate, metal, and gas phases. This problem, too, would be eliminated under zero or near zero-g conditions.

Experimental Procedure

In pre-launch operations, variously sized (0.1 - 5 mm diameter) glass spheres or sintered pellets of the silicate starting materials will be prepared and inserted into a lazy-susan sample holder. During launch, this holder, containing up to 20 samples, would permit one charge at a time to be levitated. Under relatively high ambient pressures, levitation will be accomplished acoustically; at lower pressures, electrostatic or laser levitation may be used. Samples will be levitated into the pre-heated hotspot in a Mo and W-wound furnace. They will be heated under varying conditions of time (up to 5 minutes at 2200^{o}C and up to 100 hours at 1200^{o}C), oxygen fugacity and temperature (from 1200 to 2200^{o}C). Oxygen fugacity will be controlled by circulation of a self-contained mixture of hydrogen and carbon dioxide modulated by a doped zirconia oxygen ion electrolyte. Temperatures will be controlled and determined to within 5 degrees by thermocouples located in the furnace hotspot. Analytical results will be obtained in two ways: emitted vapors will be analyzed during the runs and quenched run products will be chemically subsequently analyzed. Both quenched droplets and condensed vapor collected on cold plates will be analyzed using a variety of methods including X-ray fluorescence, microprobe, and neutron activation. In situ analyses of the effluent vapor will be carried out using UV/visible/IR absorption and fluorescence spectrometry. In addition, mass spectrometry may be useful.

System Configuration

Operating at the highest temperatures, the furnace may require as much as two kilowatts of power; however, these temperatures, run duration, and thus, peak power consumption, would last only a few (ca. 10) minutes. Insulation should be able to retain the external surface temperature of the furnace at less than 100^{o}C.

It should be possible to maintain the entire furnace assembly including levitator and gas control apparatus to less than four cubic feet. Power supply, temperature control and spectrum analyzer would require some additional space in the vicinity of the furnace. The oxygen fugacity system would require only very small volumes of hydrogen and CO_2 and would, thus, pose no safety hazard.

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TEXTURAL EVOLUTION OF PARTIALLY-MOLTEN PLANETARY MATERIALS IN MICROGRAVITY

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Scientific Rationale

Recent Earth-based experiments examining the textural evolution of partially-molten rocks have revealed two important ways in which surface energy considerations affect magma evolution. First, it is now clear that there exists a specific melt fraction (3-5% for partially-molten peridotite) that represents a bulk-system minimum in surface energy: In the absence of physical forces, this melt fraction stably persists along grain edges in a continuous, 3-dimensional network.

Secondly, in systems of initially free-floating grains, surface energy reduction may be achieved by welding together of like grains. In experiments on Earth, this process is drastically accelerated by gravitational settling of the generally denser mineral grains, which promotes grain-to-grain contact and eventual welding to form a continuous mat of crystals at the bottom of the crucible, from which most of the melt is expelled.

In microgravity environments, surface energy effects will also operate. The key point is that in low-g the surface energy effects will not be modified by gravitational considerations. Because of the energy gained by wetting of grain edges in a partially-molten rock, it may be impossible in the near-absence of gravity to extract small amounts of partial melt. Under circumstances of high melt fraction, initially dispersed crystals will make only random contact with one another; so the process of grain-to-grain welding will be slowed, perhaps giving way to some extent to grain coarsening.

For the reasons noted above, the evolution of partially-molten systems in low-g environments can be expected to be quite different from that occurring on Earth. Actual experimentation with systems experiencing low gravity is clearly needed, however, in order to appreciate fully the differences. The results of such experiments have direct applications to the magmatic evolution of small planetary bodies (and to the Earth as well in regions where neutral buoyance of crystals might occur); microgravity experiments would also provide a firm basis for interpreting the textures of such enigmatic meteorites as pallasites.

Experiments

An initial experimental program addressing surface-energy effects on partially-molten materials in microgravity would involve simple, isothermal treatment of natural samples (meteorites, peridotitic komatiite) at preselected temperatures in the melting range. Textural evolution would be assessed by time studies in which the only experiment variable would be run duration. Textural characterization of each sample would be done by quenching, recovery, and sectioning for generally later, computer-aided interpretation of features.

Requirements

A furnace capable of:

- temperature to $1800^{\circ}C$ and control to $\pm 3^{\circ}$ over entire sample

- controlled oxygen fugacity
- accommodating a 1 cubic centimeter sample
- experiment durations up to 1 month
- rapid sample quench (200° - 500°C/sec)

Highly-desirable support facilities would include a scanning electron microscope with energy-dispersive analytical capability and and on-board sample sectioning/polishing capability.

N89-15038

GRAIN DYNAMICS IN ZERO GRAVITY

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The dynamics of granular materials has proved difficult to model, primarily because of the complications arising from inelastic losses, friction, packing, and the effect of many grains being in contact simultaneously. One interesting limit for which it has recently been possible to construct a theory[1,2] is that where the grain-grain interactions are dominated by binary collisions. The kinetic model of granular systems is similar to the kinetic theory of gases, except that collisional energy losses are always present in the former and must be treated explicitly. Few granular materials on Earth are describable by this limiting model, since gravity tends to collapse the grains into a high-density state where Coulombic friction effects are dominant.

The planned Space Station offers an unusual opportunity to test the kinetic grain model and to explore its predictions. Without gravity, we will be able to investigate the regime of low interparticle velocities, where an elastic description of the collision is still valid. This will allow for direct interpretation by dynamical computer simulations as well as by kinetic theory.

One effect predicted by the kinetic theory is the tendency for inelastic grains to cluster together away from a source of energy. For instance, if one wall of a box partially filled with grains in the absence of gravity is vibrated, the density of grains close to this wall will become small, while near the opposite (cold) wall the grain density approaches its maximum value (see Figure 1a). Correspondingly, as illustrated in Figure 1b, kinetic grain models predict that grain "thermal" velocities become very small at a characteristic distance from the "hot" wall. Computer simulations of this situation also predict that the particle velocities should fall and that they should cluster away from the "hot" wall.[3]

We propose a basic experiment to be performed on the Space Station which would examine the dynamics of spherical grains inside a clear box. Data would be obtained primarily from a film of the experiment and analyzed using techniques we are presently developing. Results would be compared with the predictions of the kinetic theory and computer simulations. In addition, the effect of grain rotations would be studied.

Planetary rings can be theoretically modeled using the kinetic theory of granular dynamics.[4] We would like to use this experimental apparatus to investigate some of the parameters needed for such a model. In particular, we could study the clustering effect for realistic materials, as well as the details of individual two-body collisions.

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FIGURE CAPTIONS

Fig. 1. One wall of a box partially filled with inelastic grains is heated (the left wall in the figure). A kinetic theory of grain dynamics is used to calculate the dimensionless density (a) and the dimensionless thermal velocity (b) as a function of position in the box for seven sets of parameters. Note that for run (g), the far wall is cool but not cold.

Run	% free space in box	thermal conductivity coefficient	coefficient of restitution
a	10	1	.9
b	10	10	.9
c	50	1	.9
d	50	10	.9
e	50	1	.6
f	90	1	.6
g	90	10	.6

Figure 1a.

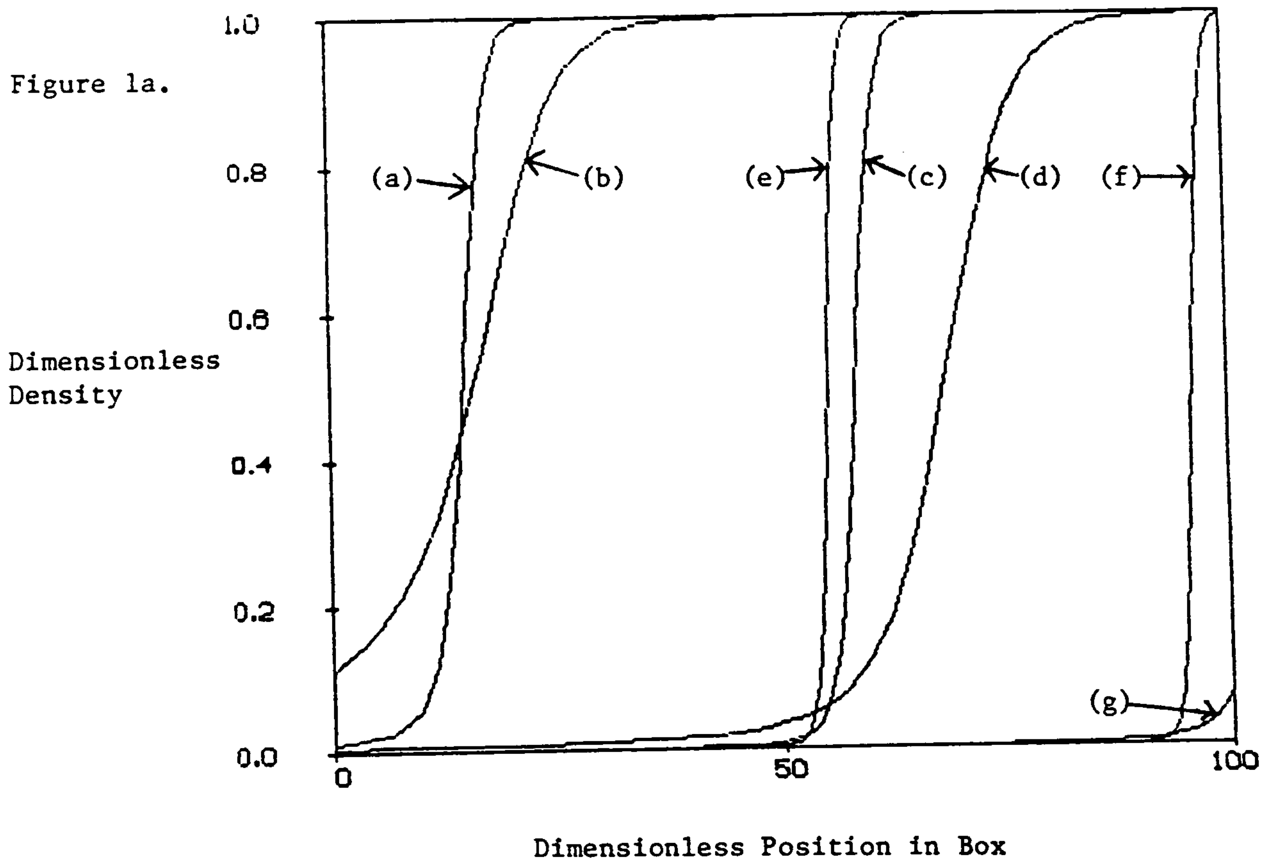
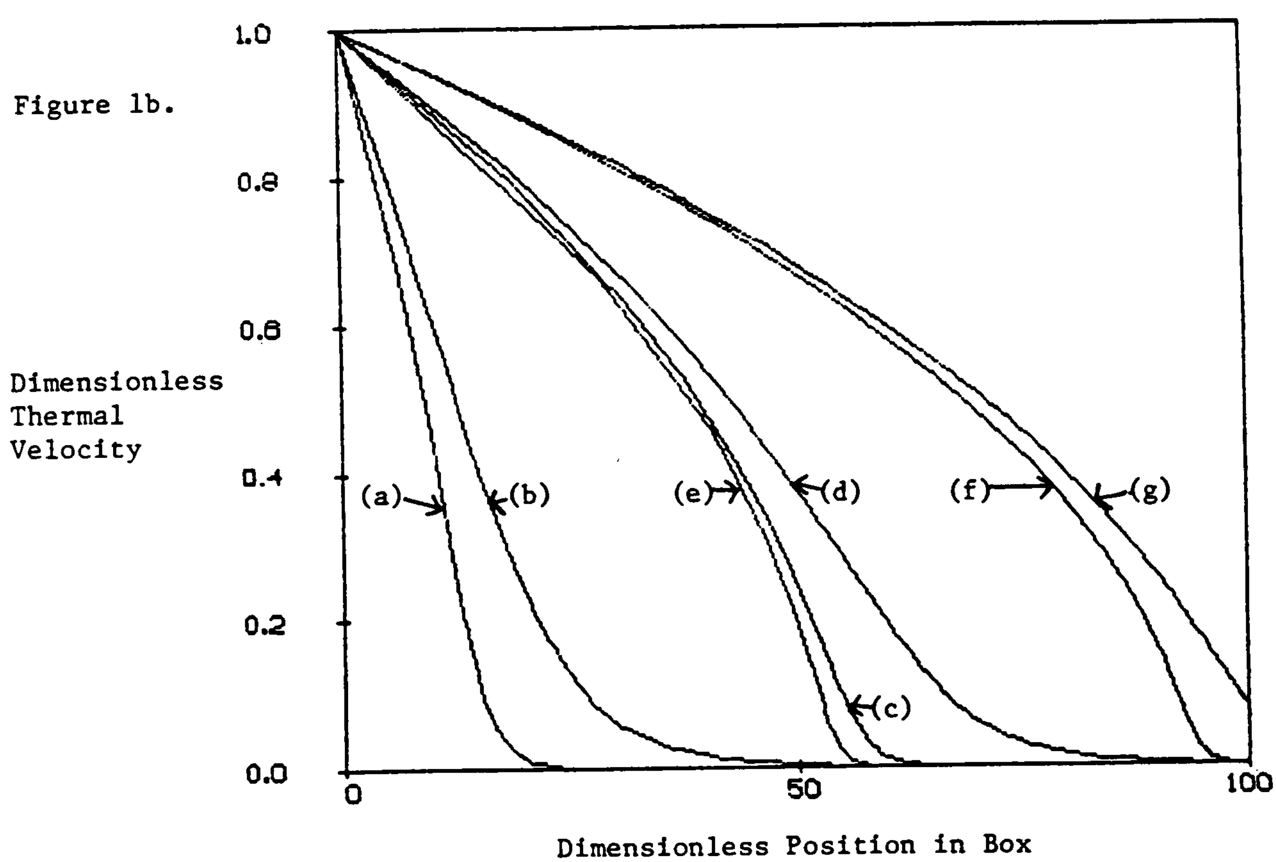


Figure 1b.



N89 - 15039

AEOLIAN PROCESSES ABOARD A SPACE STATION: SALTATION AND PARTICLE TRAJECTORY ANALYSIS

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The type of wind tunnel we propose to use to study aeolian processes aboard a space station consists of two concentric rotating drums. The space between the two drums comprises the wind tunnel test section. Differential rates of rotation of the two drums would provide a wind velocity with respect to either drum surface. Rotation of the outer drum provides a "pseudo" gravity ("pseudo" in the sense that a gravity force acts on the particle only when it is resting on the outer drum surface). This type of wind tunnel is hence referred to as a Carrousel Wind Tunnel (CWT). Preliminary results of measured velocity profiles made in a prototype (CWT) indicate that the wall bounded boundary-layer profiles are suitable to simulate flat plate turbulent boundary layer flow.

Once particles are airborne, the forces acting on individual grains in their trajectories are the particle weight and the aerodynamic lift and drag. The two-dimensional flat-plate Cartesian coordinate equations of motion of a particle moving through the air can be written as

$$\frac{4}{3}\frac{\rho_p}{\rho} D_p\ddot{x} = \dot{y}V_rC_L - (\dot{x} - u)\, V_rC_D \tag{1}$$

$$\frac{4}{3}\frac{\rho_p}{\rho} D_p\ddot{y} = -\,(\dot{x} - u)V_rC_L - \dot{y}V_rC_D - \frac{4\rho_p g D_p}{3\rho} \tag{2}$$

$$V_r^2 = (\dot{x} - u)^2 + \dot{y}^2 \tag{3}$$

The last term in Equation 2 is the weight factor. Experimental and calculated trajectories for zero and one-gravity conditions have been calculated. With the elimination of the weight factor under zero-gravity, the only forces remaining are aerodynamic. Thus, experiments conducted in zero-gravity would enable direct assessment of aerodynamic lift and drag.

In order to assess the suitability of CWT in the analysis of the trajectories of windblown particles, a series of calculations was conducted comparing cases for gravity with those of zero gravity. The equations of motion for an airborne particle, assuming no lift force, are (in a polar coordinate system, Greeley and Iversen, 1983),

$$\ddot{r} - r\,\dot{\theta}^{2} - g\cos\theta + \left(\frac{3\rho C_D \dot{r}}{4\rho_p D_p}\right) V_r = 0 \tag{4}$$

$$r\,\ddot{\theta} + 2\,\dot{r}\,\dot{\theta} + g\sin\theta - \left(\frac{3\rho C_D}{4\rho_p D_p}\right) [U(r) - r\,\dot{\theta}]\, V_r = 0 \tag{5}$$

$$V_r = \{\dot{r}^{2} + [U(r) - r\,\dot{\theta}]^2\}^{1/2} \tag{6}$$

Equations 4, 5, and 6 were solved for several example cases. The drag coefficient, C_D, is a function of Reynolds number, assuming a spherical particle (White et al., 1975). Figure 1 illustrates particle trajectories in CWT for zero-gravity atmospheric-pressure conditions. The coordinate system is fixed to the particle launch point and rotates with the outer cylinder. In inertial space the trajectories are straight lines, but relative to an observer standing on the launch point of the rotating outer drum, as plotted, the trajectories are curved. The initial inward radial velocity of the particle is assumed to be equal to the surface friction speed of the outer cylinder. The assumed wind speed profile for the calculation was taken from prototype velocity profile measurements. Since the only force acting on the particle in CWT is aerodynamic, significant differences between trajectories with and without gravity should enable much more accurate determination of the aerodynamic forces (drag and lift) than is possible in an Earth-based facility. We conclude that the CWT can yield significant data on the trajectories of windblown particles impossible to acquire under the effect of gravity.

Analyisis of particle trajectories in a zero-gravity environment would enable the determination of the aerodynamic forces on windblown particles by using high-speed motion picture obtained during the experiments. The lift and drag forces would be determined by measuring particle accelerations, particle speeds, and wind speeds, and applying Equations 4, 5, and 6 to the results.

In conclusion, results from our calculations demonstrate that a wind tunnel of the carrousel design could be fabricated to operate in a space station environment and that experiments could be conducted which would yield significant results contributing to the understanding of the physics of particle dynamics.

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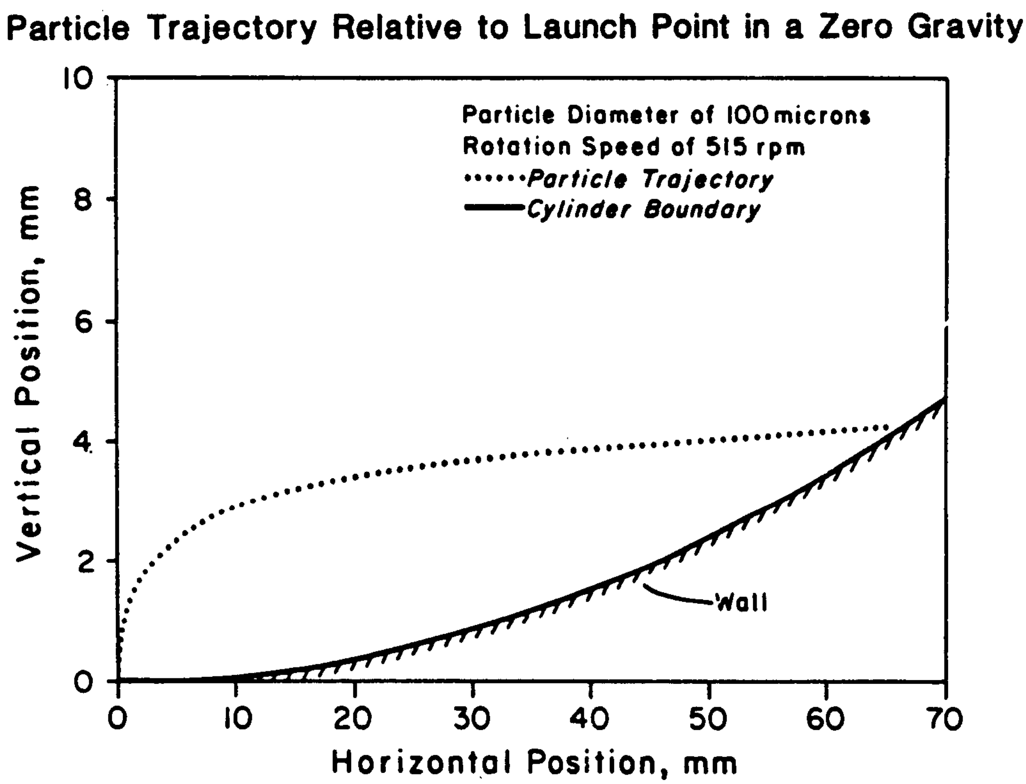

Figure 1 Calculated particle trajectory in zero-gravity, with one atmosphere of air, based on assumed drag characteristics. The outer cylinder is not rotating and the coordinate system is fixed to it at the launch point. The initial inward radial velocity of the 100 μm diameter particle is assumed to be 32.6 cm/s, the friction speed of the flow near the outer cylinder.

A SYSTEM FOR CONDUCTING IGNEOUS PETROLOGY EXPERIMENTS UNDER CONTROLLED REDOX CONDITIONS IN REDUCED GRAVITY

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The Space Shuttle and the planned Space Station will permit experimentation under conditions of reduced gravitational acceleration offering experimental petrologists the opportunity, as never before to study crystal growth, element distribution, and phase chemistry under entirely new conditions. In particular, the confounding effects of macro- and micro-scale buoyancy-induced convection and crystal settling or floatation can be greatly reduced over those observed in experiments in the terrestrial laboratory. Also, for experiments in which detailed replication of the environment is important, the access to reduced gravity will permit a more complete simulation of processes that may have occurred on asteroids or in free-space. This latter aspect may be particularly relevant to studies of petrogenesis of chondrules and other meteorite components.

Most of the geologically interesting systems contain significant amounts of redox-sensitive ions--Fe, Ti, Cr, etc.--and, thus, studies of phase relations and crystallization require control of the oxygen fugacity during the experiment. Sophisticated, but rather standardized techniques, have been developed to control, measure, and manipulate oxygen fugacity in the terrestrial laboratory. Gas mixing is the major technique used in the study of one atmosphere igneous processes; unfortunately, it is not directly adaptable to use in space experimentation, because large quantities of gas must be flowed over the sample to maintain the oxygen fugacity. It is the purpose of this paper to describe a newly developed technique that can be used to control, measure, and manipulate oxygen fugacities with small quantities of gas which are recirculated over the sample. This system could be adaptable to reduced gravity space experiments requiring redox control.

System Description

The system employs a single solid ceramic oxygen electrolyte cell for both control and measurement of the oxygen fugacity. This is possible because the electrolyte cells can be used as oxygen pumps to adjust the CO_2/CO ratio in the gases that are used to impose redox control in gas mixing systems electronically.

The system consists of a furnace surrounding a closed-end alumina muffle which surrounds a closed-end oxygen electrolyte tube that is platinized on both sides. A sample is suspended inside the electrolyte tube. Seals separate the gas in the alumina tube from the inner side of the electrolyte tube and isolate both from the laboratory atmosphere. Electrical feed-throughs connect the inner and outer electrode contacts to a DC power supply. The space between the aluminum muffle and the electrolyte cell is filled with oxygen gas (1 atmosphere pressure at $1200^{o}C$) and sealed. The inner side of the electrolyte cell is filled with a 1:1 mixture of CO and CO_2 (also at 1 atmosphere at $1200^{o}C$). This mixture is sealed off and recirculated within the inner cell by a small pump.

The oxygen fugacity is manipulated by applying a voltage to the cell and transferring oxygen in to or out of the interior volume depending on the experimental condition desired. The oxygen fugacity can be cycled between those of the quartz-fayalite-magnetite and quartz-fayalite-iron buffers in about 30 minutes at $1200^{o}C$, maintained to within 0.05 log units of a preset value over day-long periods, or changer in a controlled manner as function of temperature so that a preselected pattern is replicated during cooling or heating. The oxygen fugacity is measured by turning off the electrolysis voltage and recording the EMF with a high impedance DC millivolt meter.

A high efficiency (approximately 0.2 watts/^{o}C) furnace has been specially designed to operate on 28 VDC. At 1200^{o}C, the hot zone is 2 inches long, by 2 inches diameter. The power supply to the furnace is controlled using a standard thermocouple as a sensor. It will maintain the temperature to within less than 1^{o}C of a preselected temperature and can cool the system at controlled rates between 0.5^{o} to 100^{o}C per hour; heating rates of up to 1000^{o}C/hr are possible. The maximum operating temperature is 1350^{o}C for the current furnace.

A micro-computer is used to control both temperature and oxygen fugacity, both of which can be changed independently as a function of time. The computer also performs data acquisition tasks, and switches between the measurement and oxygen pumping modes of operation.

Experiments done conventionally and those done using this system yield identical results in a one-g gravity field.

The total system (exclusive of the computer use for laboratory control) is 4 cubic feet; it uses about 500 watts. Except for the gas used to charge the system (approximately 30 cc at STP), no gas is used during the experiment. Although water cooling is now used to control the temperature of the furnace seals, radiative cooling is probably possible.

Summary

A system directly adaptable for use in controlled oxygen fugacity experimentation on Shuttle or Space Station has been designed, built, and tested. It should permit reduced gravity experiments which require such control to be undertaken.

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NEW TECHNIQUES FOR THE DETECTION AND CAPTURE OF MICROMETEOROIDS

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In order to understand the origin and distribution of the biogenic elements and their compounds in the solar system, it will be necessary to study material from many classes of objects. Chemical, elemental, and isotopic measurements of returned samples of comets, asteroids, and possibly extra-solar system dust clouds would provide information on a particularly important class: the primitive objects. Extraterrestrial micron-sized particles in the vicinity of Earth are one source of such materials that might otherwise be inaccessible. The Space Station appears to be an eminently suitable platform from which to collect and detect these various particles. The primary challenge, however, is to collect intact, uncontaminated particles which will be encountered at tens of kilometers per seconds.

A concept for a micrometeoroid detector that could be deployed from Space Station has been developed which uses a large area detector plate implanted with acoustic transducers. When an impact event occurs, the resulting signal is subjected to spectral analysis providing positive detection, momentum information, and angle of incidence. The primary advantage of this detector is the large area which increases the probability of measuring events. A concept of a nondestructive micrometeoroid collector for use from Space Station has also been developed. The collector utilizes input port charging of the incoming particle followed by staged high voltage deceleration for nondestructive capture. Low velocity particles (local contamination) would be rejected due to insufficient energy and only uncontaminanted micrometeoroids would be collected. Particles so collected would then be returned to Earth for subsequent analysis.

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EXPERIMENTAL CONSTRAINTS ON HEATING AND COOLING RATES OF REFRACTORY INCLUSIONS IN THE EARLY SOLAR SYSTEM

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The refractory inclusions in carbonaceous chondrites have been the subject of considerable interest since their discovery. These inclusions contain minerals that are predicted to have been some of the earliest condensates from the solar nebula, and contain a plethora of isotopic anomalies of unknown origin. Of particular interest are those coarse-grained inclusions that contain refractory metal particles (Fe, Ni, Pt, Ru, Os, Ir).

Experimental studies of these inclusions in terrestrial laboratories are, however, complicated because the dense particles tend to settle out of a molten or partially molten silicate material. Heating experiments in the Space Station environment would take advantage of "containerless" furnace technology and microgravity in order to observe the effects of metal nuggets (which may act as heterogeneous nucleation sites) on nucleation rates in silicate systems and to measure simultaneously the relative volatilization rates of siderophile and lithophile species (also see Walter Volatilization-Fractionation. . . .This Report). Neither experiment is possible in the terrestrial environment.

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EXPERIMENTAL CONSTRAINTS ON THE ORIGIN OF CHONDRULES

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Chondrule formation must have been an important (perhaps ubiquitous) process in the early solar system, yet their origins remain elusive. Some points, however, are clear. The precursor material of chondrules (dust?) was rapidly heated at rates of perhaps thousands of degrees per second and was cooled more slowly (0.1-1.0^{o}C/sec), (also see Nuth, Nucleation Experiments. . . ., This report).

We propose to investigate chondrule formation in the Space Station environment via a "dust-box" - a chamber (~1 m^3) in which dust can be suspended, heated, and cooled. A microgravity environment is conducive to this kind of experiment because of the significant retardation of settling rates compared with a terrestrial laboratory environment. These long-duration experiments might require the development of technologies to counteract even the small, but finite and permanent gravitation field of the Space Station.

Simple, but interesting experiments on dust suspensions immediately present themselves. For heating events of less than 1 second (using a laser, multiple lasers, or electrical discharge), what dust density is required to produce large

(0.1-1.0 mm) objects? Is the density so large that chondrules cannot cool quickly? What conditions are necessary to mimic observed textures in chondrules?

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EXPERIMENTAL CORRELATION OF MELT STRUCTURES, NUCLEATION RATES, AND THERMAL HISTORIES OF SILICATE MELTS

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The theory and measurement of the structure of liquids is an important aspect of modern metallurgy and igneous petrology. Liquid structure exerts strong controls on both the types of crystals that may precipitate from melts and on the chemical composition of those crystals. An interesting aspect of melt structure studies is the problem of melt "memories"; that is, a melt can retain a memory of previous thermal history. This memory can influence both nucleation behavior and crystal composition.

This melt memory may be characterized quantitatively with techniques such as Raman, infrared and NMR spectroscopy to provide information on short-range structure. Melt structure studies at high temperature will take advantage of the microgravity conditions of the Space Station to perform containerless experiments. Melt structure determinations at high temperature (experiments that are greatly facilitated by containerless technology) will provide invaluable information for materials science, glass technology and geochemistry. In conjunction with studies of nucleation behavior and nucleation rates, information relevant to nucleation in magma chambers in terrestrial planets will be acquired.

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"CONTAINERLESS" HIGH-PRESSURE PETROLOGY EXPERIMENTS IN THE MICROGRAVITY ENVIRONMENT OF THE SPACE STATION

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Problem

The genesis of igneous rocks on terrestrial planets can only be understood through experiments at pressures corresponding to those in planetary mantles (10-50 kbar). Such experiments typically require a piston-cylinder apparatus, and apparatus that has the advantage of controllable pressure and temperature, adequate sample volume, rapid sample quench, and minimal danger of catastrophic failure. The experimental charge must be prevented from touching the walls of the cylinder and so is usually encased in a capsule of platinoid metal or alloy. Unfortunately, the platinoid containers usually can dissolve significant Fe (and other transition metals) from the experimental charge (at the oxygen fugacities appropriate for magma genesis) and, thus, results in alteration of the chemical composition of the charge. The strategies available to eliminate this problem in terrestrial laboratories reduces the applicability of the results of realistic natural conditions.

Solution

We propose to perform high-pressure and -temperature, piston-cylinder experiments aboard the Space Station. The microgravity environment in the Space Station will minimize settling due to density contrasts and may, thus, allow experiments of moderate duration to be performed without a platinoid capsule and without the sample having to touch the container walls. The ideal pressure medium would have the same temperatures. It is emphasized, however, that this proposed experimental capability requires technological advances and innovations not currently available.

N89-15046

MAPPING EXPERIMENT WITH SPACE STATION

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Mapping the Earth from space stations can be approached in two areas. One is to collect gravity data for defining a new topographic datum using Earth's gravity field in terms of spherical harmonics. The geoid produced by this experiment may be much closer to the reality of Earth's equipotential surface than that which is currently used. Due to the fact that the Earth is both longitudially and latitudially asymmetric as indicated in the results of gravity studies by Votila (1962), this proposed experiment may be useful for a new generation of Earth mapping. The other, which should be considered as very significant contribution from the space station, is to search and explore techniques of mapping Earth's topography using either optical or radar images with or without reference to ground control points. Without ground control points, an integrated camera system can be designed. The system, in addition to the imaging camera, will consist of a stellar camera, radar altimeter and an inertial platform such as the one which was installed on the AN/USQ-28 Mapping and Survey Subsystem (Livingston et al., 1980). With ground control points, the position of the space station (camera station) can be precisely determined at any instant. Therefore, terrestrial topography can be precisely mapped either by conventional photogrammetric methods or by current digital technology of image correlation.

At an altitude of 300 km, the space station can view an area on the surface of Earth, that is intersected by a cone with a solid angle of 34.5° with respect to the Earth's center. Theoretically, if a total of 44 permanent ground-control points can be ideally distributed on the Earth's surface such that: 12 points along the equator with longitude increment of 30°; 18 points along latitude + and - 30° with longitude increment of 40°; 12 points along latitude + and - 60° with longitude increment of 60°; and 1 point at each of the two poles, then at least 3 ground control points can be viewed by the space station at any instant and its position (camera station) can be determined by resection with electronic ranging measurements. But, practically, permanent ground-control points in oceans are difficult to be established, distribution of permanent control points have to be adjusted on continents and islands. Geodetic position of ground control points can be predetermined by the Global Positioning System (GPS). In order to continue the radar experiment of the planned SIR-C mission, corner reflectors of right-angle tetrahedron can be installed at all ground control points.

With a radar altimeter on board, profiles traced along tracks of the space station can be utilized for constraints in addition to the determined position of the space station for photogrammetric processing.

For the mapping experiment with the space station, I propose to establish four such ground control points either in North America or Africa (including the Sahara desert). If this experiment should be successfully accomplished, it may also be applied to our defense charting systems.

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16. Abstract

During the last several years, studies have been undertaken to identify the potential science activities that could be conducted in the environment afforded by an Earth-orbiting space station. Activities related to planetary science that are being considered for the Space Station include using the Station (1) as a platform for planetary observations, (2) as a staging base for various lunar and planetary missions, (3) to collect "dust," and (4) as an environment for carrying out experiments. This report concerns the fourth topic.

Many planetary environments involve gravitational accelerations less than that of Earth. The Space Station could enable experiments to be conducted in which gravity (g) is a critical term in certain planetary processes, especially for planetary experiments requiring extremely low gravity environments such as comets and asteroids. In other experiments, g may not be a critical term for study, but its near-absence on Space Station may enable experiments to be conducted which cannot be done on Earth. Some of the general experiment areas that have been suggested include impact cratering, experimental petrology, and the formation and interaction of small particles (e.g., planetary ring dynamics).

Numerous workshops were held to provide a forum for discussing the full range of possible experiments, their science rationale, and the requirements on the Space Station, should such experiments eventually be flown. These workshops, sponsored by NASA through Arizona State University and the Lunar and Planetary Institute, were open to all interested scientists. During the workshops, subgroups met to dis cuss areas of common interest (impact cratering, aeolian processes, particle formation and interaction, and planetary materials/miscellaneous). This report includes summaries of each group and abstracts of contributed papers as they developed from a workshop on September 15-16, 1986.

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